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16. ABSTRACT

A dispersion model has been developed for pollutant discharges from the Buccaneer Oil Field in the Gulf of Mexico. The model requires input data for subsurface currents, wind speed and direction, platform geometry, pollutant source strength, and particle size distribution, at regular time intervals. The distributions of floating, sinking, and vertically mixed pollutants are calculated separately. Output from the model includes graphs which show the growth of the turbulent wake downstream from the platform, the change in pollutant concentrations over time and distrance transported, trajectories of floating and subsurface pollutants, and settling times for particles of various sizes. Sample data were run for six different two-day periods, three in winter and three in summer. The results indicate rapid dispersion, and long-range transport of minute quantities of pollutants. Pollutants were transported much greater distances in winter than in summer, with floating pollutants having the capability to reach the coast southwest of Galveston within about two days. (Author modified)

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VOL.X - HYDRODYNAMIC MODELING

BY

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A report to the Environmental Protection Agency on work conducted under provisions of Interagency Agreement EPA-IAG-D5-E693-E0 during 1978-1979.

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Volume X - HYDRODYNAMIC MODELING

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LIST OF VOLUMES

This Annual Report is printed in ten separate volumes:

Volume I - SYNOPSIS/DATA MANAGEMENT

Work Unit 2.6.1	Synopsis NMFS/SEFC Galveston Laboratory Principal Investigators
Work Unit 2.2.3	Implement, Monitor, and Modify Data Management System NMFS/SEFC National Fisheries Engineering Laboratory K. Savastano H. Holley

Volume II - SEDIMENTS AND PARTICULATES

Work Unit 2.3.2	Investigations of Surficial Sediments and Suspended Particulates at Buccaneer Field Texas A&M University J. Brooks, Ph.D. E. Estes, Ph.D. W. Huang, Ph.D.

Volume III - FISHES AND MACROCRUSTACEANS

Work Unit 2.3.5	Effect of Gas and Oil Field Structures and Effluents on Pelagic and Reef Fishes, Demersal Fishes, and Macrocrustaceans LGL Ecological Research Associates, Inc. B. Gallaway, Ph.D. L. Martin

Volume IV - BACTERIA

Work Unit 2.3.7	Bacterial Communities University of Houston R. Sizemore, Ph.D. K. Olsen

Volume V - FOULING COMMUNITY

Work Unit 2.3.8	Effects of Gas and Oil Field Structures and Effluents on Fouling Community Production and Function LGL Ecological Research Associates, Inc. R. Howard G. Boland B. Gallaway, Ph.D. G. Dennis

Volume VI - CURRENTS AND HYDROGRAPHY

Work Unit 2.3.9	Currents and Hydrography of the Buccaneer Field and Adjacent Waters Hazleton Environmental Sciences Corporation L. Danek, Ph.D. M. Tomlinson

Volume VII - HYDROCARBONS

Work Unit 2.4.1	Hydrocarbons, Biocides, and Sulfur University of Houston B. Middleditch, Ph.D. D. West

Volume VIII - TRACE METALS

Work Unit 2.4.2	Trace Metals
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Volume IX - FATE AND EFFECTS MODELING

Work Unit 2.5.1	Sources, Fate and Effects Modeling
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Volume X - HYDRODYNAMIC MODELING

Work Unit 2.5.2	Hydrodynamic Modeling
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	G. Smedes, Ph.D. J. Calman J. Beebe

GUIDE TO USERS OF THE ANNUAL REPORT

Volume I (SYNOPSIS/DATA MANAGEMENT) of the Annual Report is designed to be used as a briefing document and as a key to more detailed scientific and technical information contained in Volumes II through X. Objectives, methods and results for each work unit are summarized in greatly abbreviated form within Volume I to facilitate dissemination of information. Thus, Volume I can be used alone or as a reference to companion Volumes II through X. Complete citations for literature cited in Volume I can be found in the Volumes II through X in which the detailed work unit reports are presented.

It is hoped that such an approach to environmental impact information dissemination will make the Annual Report a more useful and widely read document.

FOREWORD

Increased petroleum development of the outer continental shelf (OCS) of the United States is anticipated as the U.S. attempts to reduce its dependency on foreign petroleum supplies. To obtain information concerning the environmental consequences of such development, the Federal Government has supported major research efforts on the OCS to document environmental conditions before, during, and after oil and gas exploration, production, and transmission. Among these efforts is the Environmental Assessment of Buccaneer Gas and Oil Field in the Northwestern Gulf of Mexico, a project funded by the Environmental Protection Agency (EPA) through interagency agreement with the National Oceanic and Atomospheric Administration (NOAA) and managed by the National Marine Fisheries Service (NMFS), Southeast Fisheries Center (SEFC), Galveston Laboratory, in Galveston, Texas. Initiated in the autumn of 1975, the study is now in its last year. Its major products have been annual reports disseminated by the National Technical Information Service, data files archived and disseminated by NOAA's Environmental Data and Information Service, and research papers written by participating investigators and published in scientific or technical journals. Results have also been made available through EPA/NOAA/NMFS project reviews and workshops attended by project participants, and various governmental (Federal and State), private, and public user groups. The final products will be milestone reports summarizing the findings of the major investigative components of the study.

Objectives of the project are (1) to identify and document the types and extent of biological, chemical and physical alterations of the marine ecosystem associated with Buccaneer Gas and Oil Field, (2) to determine specific pollutants, their quantity and effects, and (3) to develop the capability to describe and predict fate and effects of Buccaneer Gas and Oil Field contaminants. The project uses historical and new data and includes investigations both in the field and in the laboratory. A brief Pilot Study was conducted in the autumn and winter of 1975-76, followed by an extensive biological/chemical/physical survey in 1976-77 comparing the Buccaneer Gas and Oil Field area with adjacent undeveloped or control areas. In 1977-78, investigations were intensified within Buccaneer Gas and Oil Field, comparing conditions around production platforms, which release various effluents including produced brine, with those around satellite structures (well jackets) which release no effluents. In 1978-79, studies around Buccaneer Gas and Oil Field structures focused on (1) concentrations and effects of pollutants in major components of the marine ecosystem, including seawater, surficial sediments, suspended particulate matter, fouling community, bacterial community, and fishes and macro-crustaceans, (2) effects of circulation dynamics and hydrography on distribution of pollutants, and (3) mathematical modeling to describe and predict sources, fate and effects of pollutants. The final year, 1979-80, of study is continuing to focus on items (1) and (2) and on preparation of the milestone reports which will represent the final products of this study.

This project has provided a unique opportunity for a multiyear investigation of effects of chronic, low-level contamination of a marine ecosystem associated with gas and oil production in a long-established field. In many respects, it represents a pioneering effort. It has been made possible through the cooperation of government agencies, Shell Oil Company (which owns and operates the field) and various contractors including universities and private companies. It is anticipated that the results of this project will impact in a significant way on future decisions regarding operations of gas and oil fields on the OCS.

Charles W. Caillouet, Project Manager
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Editors

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INTRODUCTION

Location of Study Area

The area selected for study is the operational Buccaneer Gas and Oil Field located approximately 49.6 kilometers (26.8 nautical miles) south southeast of the Galveston Sea Buoy off Galveston, Texas (Figure 1). This field was selected in 1975 as the study area because: (a) the field had been in production for about 15 years, which time had allowed full development of the associated marine communities; (b) it was isolated from other fields which facilitated the selection of an unaltered area (for comparison) within a reasonable distance of the field; (c) it produced both gas and oil that represented sources of pollutants from marine petroleum extraction; (d) its location simplified logistics and reduced the cost of the research; and (e) the Texas offshore area had not been fully developed for gas and oil production but was expected to experience accelerated exploitation in the future.

Operation History of Buccaneer Field

Buccaneer Field was developed by Shell Oil Company in four offshore blocks leased in 1960 and 1968 as follows:

Year	Lease Number	Block Number	Acreage	Hectares
1960	G0709	288	2,790	1,129
1960	G0713	295	4,770	1,930
1960	G0714	296	4,501	1,821
1968	G1783	289	2,610	1,056

In development of the field, 17 structures were built; two are production platforms, two are quarters platforms, and 13 are satellite structures surrounding well jackets. Initial exploratory drilling began about mid-summer of 1960 with mobile drilling rigs. When (as the result of the exploratory drilling) proper locations for platforms were selected, the permanent production platforms were constructed.

There have been no reports of major oil spills from this field. There have been some reported losses of oil due to occasional mechanical failure of various pieces of equipment. The largest

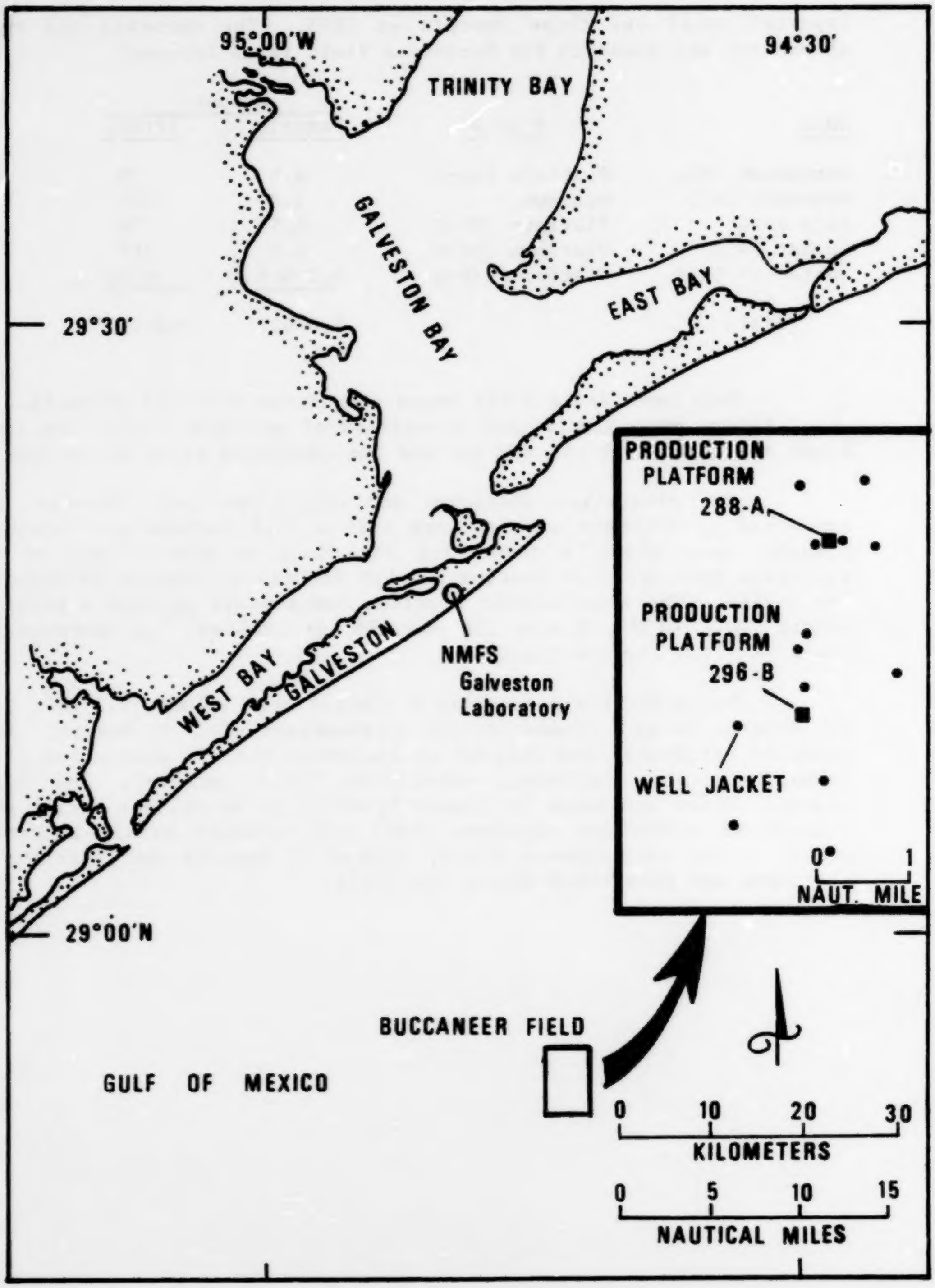
95°00'W
94°30'
TRINITY BAY
GALVESTON BAY
EAST BAY
29°30'
PRODUCTION PLATFORM
288-A
PRODUCTION PLATFORM
296-B
WELL JACKET
0
1
NAUT. MILE
NMFS Galveston Laboratory
WEST BAY
GALVESTON
29°00'N
BUCCANEER FIELD
GULF OF MEXICO
0
10
20
30
KILOMETERS
0
5
10
15
NAUTICAL MILES

FIGURE 1. LOCATION OF BUCCANEER FIELD

reported spill was three barrels in 1973. The reported oil spill chronology and quantity for Buccaneer Field is as follows:

Date	Source	Amount Barrels	Liters
September 1973	Platform 296-B	0.5	79
November 1973	Unknown	3.0	477
July 1974	Platform 296-B	0.5	79
August 1974	Platform 296-B	1.7	265
September 1975	Platform 288-A	0.2-0.4	38-56
Totals		5.9-6.1	938-956

Buccaneer Field first began operations with the production of oil. Later, when significant quantities of gas were found, the field began producing both oil and gas and has continued to do so to date.

The production platforms and satellites (well jackets) are connected by a number of pipelines with a 50.8 centimeters (20-inch) diameter main pipeline connecting the field to shore. All of the pipelines that are 25.4 centimeters (10 inches) or greater in diameter are buried. The Blue Dolphin Pipeline Company was granted a pipeline permit (No. G1381, Blocks 288 and 296) in 1965 and has operated the pipeline since its construction.

Buccaneer Field occupies a limited area (about 59.3 km^2; 22.9 sq. statute miles) leased in the northwestern Gulf of Mexico. Four types of structures are located in Buccaneer Field: production platforms, quarters platforms, satellites (well jackets), and flare stacks. These are shown in Figure 2, which is an oblique aerial photograph of production platform 288-A and vicinity within Buccaneer Field. A map of Buccaneer Field, (Figure 3) depicts the locations of platforms and satellites within the field.

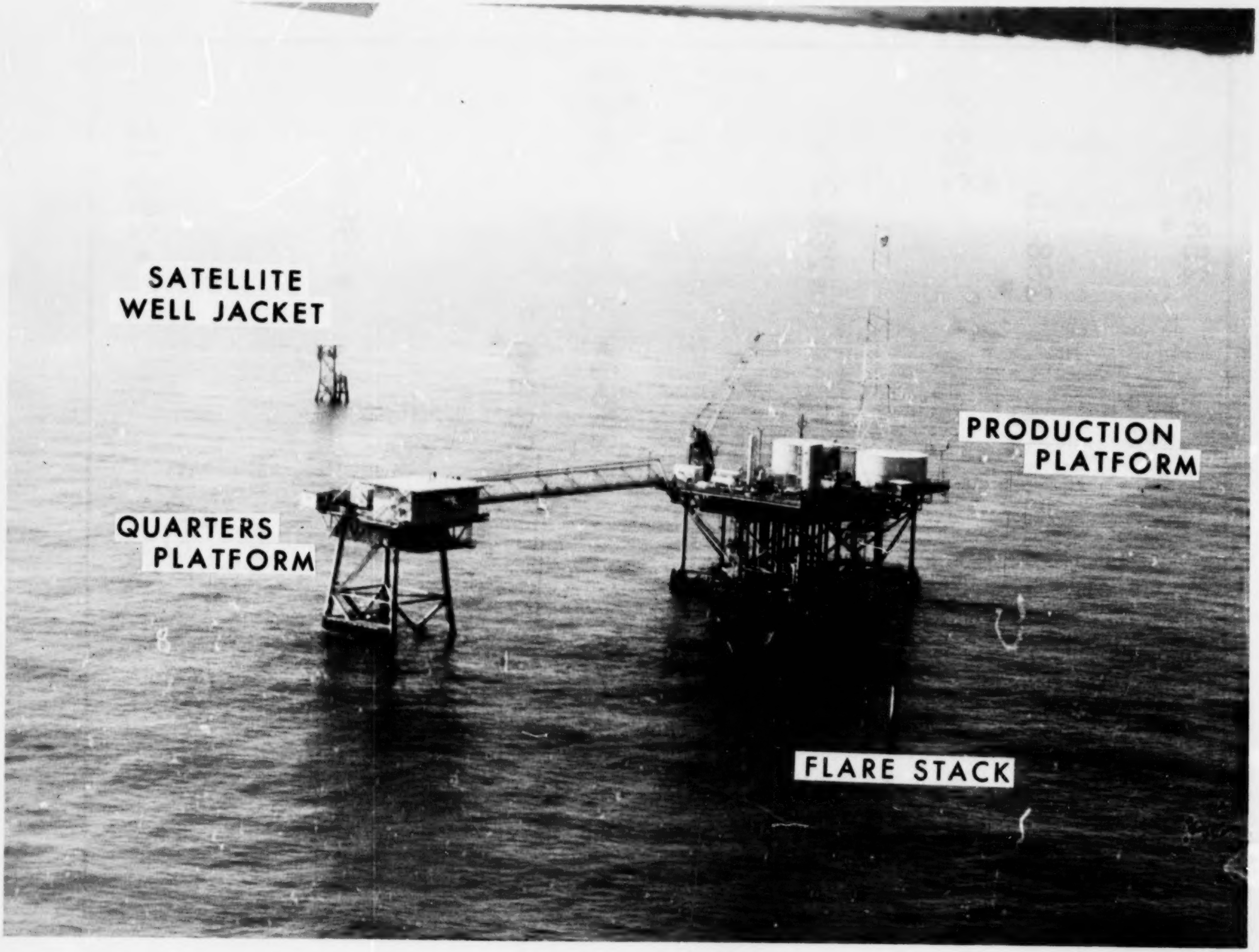
SATELLITE
WELL JACKET
QUARTERS
PLATFORM
PRODUCTION
PLATFORM
FLARE STACK

FIGURE 2. BUCCANEER FIELD STRUCTURES

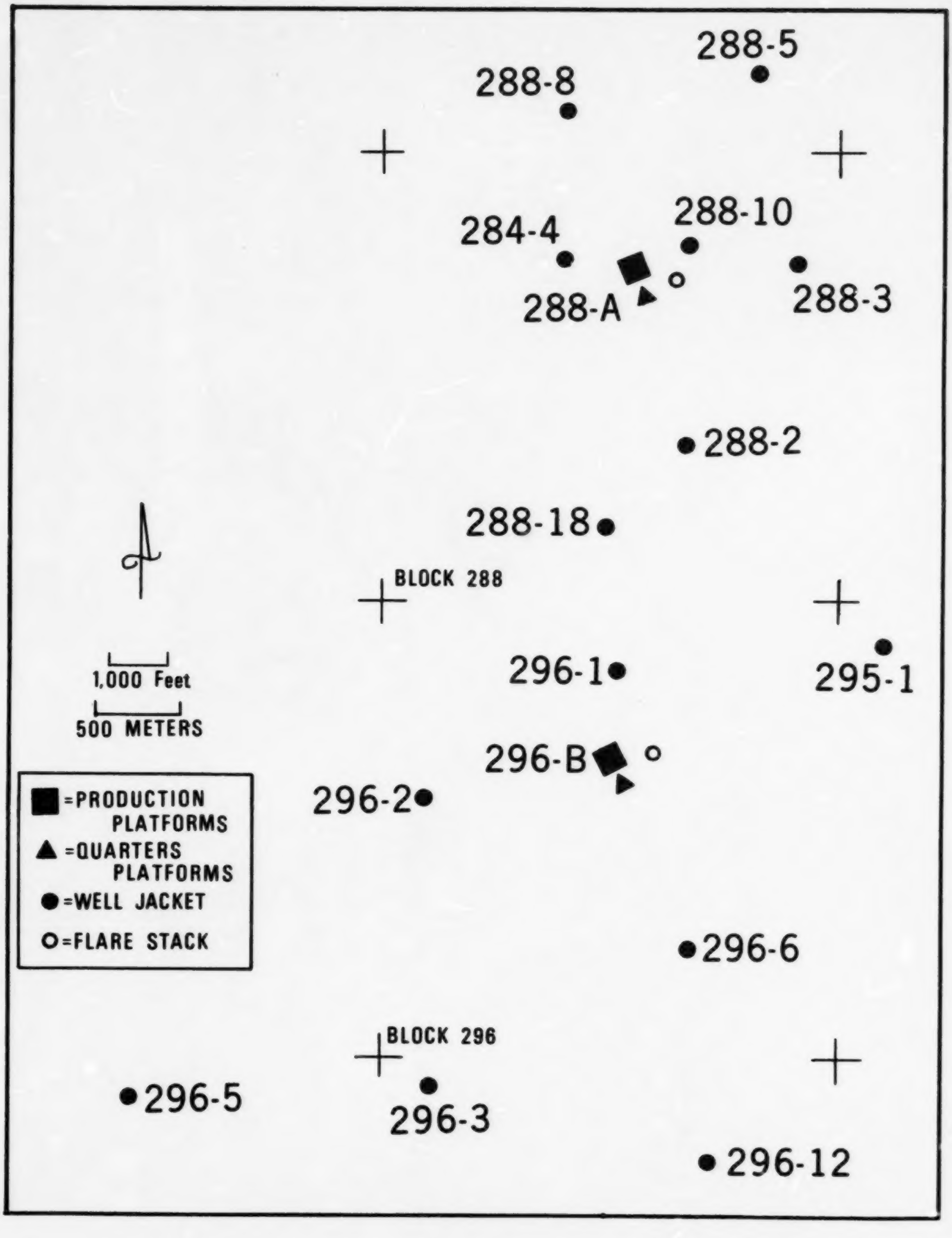
288-5
288-8
284-4
288-10
288-A
288-3
288-2
288-18
BLOCK 288
296-1
295-1
1,000 Feet
500 METERS
296-B
296-2
■ =PRODUCTION PLATFORMS
▲ =QUARTERS PLATFORMS
● =WELL JACKET
○ =FLARE STACK
296-6
BLOCK 296
296-5
296-3
296-12

FIGURE 3. SHELL OIL COMPANY'S ALPHANUMERICAL IDENTIFICATION OF BUCCANEER GAS AND OIL FIELD STRUCTURES

WORK UNIT 2.5.2 - HYDRODYNAMIC MODELING

Environmental Research and Technology, Inc.

G. Smedes, Ph.D.
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and
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ABSTRACT

A dispersion model has been developed for pollutant discharges from the Buccaneer Oil Field in the Gulf of Mexico. The model requires input data for subsurface currents, wind speed and direction, platform geometry, pollutant source strength, and particle size distribution, at regular time intervals. The distributions of floating, sinking, and vertically mixed pollutants are calculated separately. Dispersion in the near field (< 1 km from the platform) includes initial mixing produced by turbulence from the platform structure. Far-field effects (> 4 km) are based upon the similarity theory of turbulence, and conservative matching conditions are applied for intermediate distances. For floating pollutants, the model calculates the transport induced by wind drift currents. The computer program uses the conventional specification of 3.5% of wind speed for these currents, and also incorporates a time delay for wind-current equilibrium.

Output from the model includes graphs which show the growth of the turbulent wake downstream from the platform, the change in pollutant concentrations over time and distance transported, trajectories of floating and subsurface pollutants, and settling times for particles of various sizes. Sample data were run for six different two-day periods, three in winter and three in summer. The results indicate rapid dispersion, and long-range transport of minute quantities of pollutants. Pollutants were transported much greater distances in winter than in summer, with floating pollutants having the capability to reach the coast southwest of Galveston within about two days.

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LIST OF ABBREVIATIONS

km	kilometer
gm	gram
s	second
cm	centimeter
t	time
z	water depth
m	meter
ppm	parts per million
hr	hour

1. INTRODUCTION

The purpose of the Buccaneer Oil Field Platform Dispersion Model is to help in the assessment of the environmental impact of pollutants released during the normal operation of the platform. An operational hydrodynamic model is needed to quantify the distributions of various kinds of pollutants in space and time in the marine ecosystem, and to predict how these will ultimately impinge upon and be absorbed by the system.

After reviewing existing near-field, circulation and dispersion models, ERT believed that several models developed at M.I.T. (the CAFE and DISPER Series) were best suited to provide the framework for hydrodynamic modeling of the Buccaneer Oil Field (BOF). However, initial efforts with these models indicated operational difficulties and a high cost in computer time to run the programs. Since these constraints were incompatible with the needs and resources of the National Marine Fisheries Service's BOF Study program, an alternate approach was pursued.

The hydrodynamic model developed by ERT is used to describe the area which might be affected by floating and sinking pollutants, and to predict the concentrations of pollutants which are vertically distributed in the water column. For the latter pollutants, separate analytical procedures are used for near-field (<1km) and far-field (>4km) distances from the platform, with conservative estimations for pollutant concentrations at intermediate distances. The model is designed to operate in a time sequential mode, using input wind and subsurface current data at each time step. Several other parameters which describe the geometry and the nature of the discharge are also required.

The first part of this report describes the technical base upon which the model is built, including the assumptions and equations used in the calculations. The next section provides a detailed description of the model, and a user's manual for the computer program. Finally, some representative results are given, and their significance to the BOF study are discussed.

2. POLLUTANT DISPERSION

2.1 Introduction

Pollutants discharged from the Buccaneer Oil Field platform will be dispersed in different ways, depending upon their solubility, density, and size of particles, among other properties. This model does not attempt to describe in detail the fate of specific pollutants nor their detailed vertical distribution in the water column. The model describes the dispersion of three classes of pollutants, namely: those which mix thoroughly and are distributed vertically in the water column; those which float on the surface of the water; and those which sink to the bottom. The dispersion of each class of pollutant is described separately below.

2.2 Pollutants Distributed in the Water Column

Initial Mixing

Mixing of a pollutant discharged from the platform is affected by the wake created by the platform's structural members. Because of the complicated structure of the platform, mixing in the wake can be described only approximately. As the discharge is swept past the platform, it is mixed with the ambient water because of the complicated flow patterns and wakes around the individual structural members of the platform. Dye discharge experiments described at the Houston conference have shown that a dye discharged at the platform will be mixed in a volume of water approximately equal to 1/8 of the volume occupied by the platform by the time it emerges on the downstream side of the platform. Using this information, the initial concentration of pollutant in the neighborhood of the platform can be estimated as follows: Let Q (gm/s) be the rate of discharge of mass of pollutant, U (cm/s) be the ambient current, L be the length of the platform and z the water depth. The time, t, for the pollutant to be swept past the platform is:

$$t = \frac{L}{U} \qquad 2.1$$

During this time the mass, M, of pollutant discharged is:

$$M = Qt = \frac{QL}{U} \qquad 2.2$$

This mass of pollutant is mixed initially into a volume, V_o, of water approximately equal to:

$$V_o = \frac{1}{8} L^2 z \qquad 2.3$$

leading to an initial concentration, χ_o,

$$\chi_o = \frac{M}{V_o} = \frac{8Q}{(ULz)} \qquad 2.4$$

For example, the values $U = 5$ cm/s, $L = 50$m, $z = 20$m, give

$$\chi_o = 1.6 \times 10^7 Q \qquad 2.5$$

With the discharge Q estimated as 100 gm/s, the initial concentration is $\chi_o = 16$ ppm.

Dispersion in the Near Field

Observations of the expansion of a patch of dye introduced into the water about 2 km from the platform have revealed seasonal variations in the dispersion pattern (R. Armstrong, pers. comm.). Although the shape of the dye patch is elliptical, an "equivalent radius", r, may be defined so that the area, A, of the dye patch is given by $A = \pi r^2$. Some of Armstrong's observations on the rate of change of the equivalent radius, $\dot{r}$, and of the depth of penetration of the dye, h, are listed below.

	Summer	Fall	Winter	Spring*
$\dot{r}$ (m/hr)	54	21	30	42
h (m)	5	7	10	7.5

---

*Measurements were not made in spring. The values listed are averaged summer and winter values.

If an injection of a dye (or discharge of a pollutant) results in an initial mixed volume V_o of concentration χ_o, then at a later time,

$$\frac{\chi}{\chi_o} = \frac{V_o}{V} \qquad 2.6$$

Knowing the rate of expansion and depth of penetration, we can estimate

$$V = \pi(\dot{r}t)^2 h \qquad 2.7$$

so that

$$\frac{\chi}{\chi} = \frac{V_o}{\pi(\dot{r}t)^2 h} \qquad 2.8$$

Combining 2.3 and 2.7 we have,

$$\frac{\chi}{\chi_o} = \frac{L^2 z}{8\pi h \dot{r}^2 t^2} \qquad 2.9$$

an expression valid in any consistent set of units. The dye dispersion observations were made over several hours, say t_o, so the formula should be valid for any time $t \leq 3$ hours.

Mixing Downstream from the Platform

Downstream of the immediate vicinity of the platform, mixing occurs in the turbulent wake of the platform. This mixing is described by similarity theory. Taking L as the width of the platform, similarity theory predicts, at downstream distances x such that

$$\frac{x}{L} \geq 80 \qquad 2.10$$

the half-width ℓ of the wake increases as

$$\frac{\ell}{L} = \frac{1}{4}\left[\frac{2x}{L}\right]^{1/2} \qquad 2.11$$

(Tennekes and Lumley, 1972). The concentration, χ, of pollutant in the far wake is determined from the relationship,

$$\frac{\chi}{\chi_o} = \left[\frac{2x}{L}\right]^{-1/2} \qquad 2.12$$

(Monin and Yaglom, 1974).

With L = 50 m, then at a downstream distance of

$$x = \left(\frac{x}{L}\right) L = 80\ (50m) = 4 \times 10^3 m \qquad 2.13$$

from the platform, the maximum concentration occurring in the wake of width

$$2\ell = \frac{1L}{2}\left(\frac{2x}{L}\right)^{1/2} = 320m \qquad 2.14$$

is

$$\chi = 0.08\ \chi_o \qquad 2.15$$

With the example emission rate of Q = 100 gm/s, then, the concentration at distance x = 4km downstream in the wake is

$$\chi = 1.3 \text{ ppm} \qquad 2.16$$

This concentration is very approximate; by the time the pollutant has travelled so far downstream, other effects of wind and settling come into play.

Matching Conditions

Before these far-field approximations can be used, however, they must be matched to the near-field approximations given above so that the computed concentrations are continuous. The near-field approximations may be written (see 2.8):

$$\hat{X}_N = A_s t^{-2} \tag{2.17}$$

where A_s is a constant which varies with the season and $\hat{x} = x/x_o$. This approximation is valid for several hours. The far-field approximation may be written (from 2.12) as

$$\hat{X}_F = C_s \, (\hat{x})^{-1/2} \tag{2.18}$$

where C_s is a constant which depends upon the season and $\hat{x} = x/L$. This approximation is valid after about 4 km from the platform. These solutions must now be matched as follows. Suppose that at some distance $\hat{x}_M$ it is required that the two computed concentrations be the same, that is,

$$\hat{X}_N = \hat{X}_F \quad \text{at} \quad \hat{x} = \hat{x}_M \tag{2.19}$$

$$A_s t^{-2} = C_s \, \hat{x}_M^{-1/2}$$

$$\text{or } C_s = A_s t^{-2} \, \hat{x}_M^{1/2} = \hat{X}_N \, \hat{x}_M^{1/2} \tag{2.20}$$

Back-substitution gives

$$\hat{X}_F = \hat{X}_N \left[\frac{\hat{x}_M}{\hat{x}} \right]^{1/2} \tag{2.21}$$

Combining all results

$$\hat{X} = \begin{cases} \hat{X}_N & \hat{x} < \hat{x}_M \\ \hat{X}_N \left(\hat{x}_M / \hat{x} \right)^{1/2} & \hat{x} \geq \hat{x}_M \end{cases} \tag{2.22}$$

It remains to determine the matching distance, $\hat{x}_M$. The far-field solution is assumed for $x \geq 4$ km, and the near-field solution is assumed valid for several hours. For a typical current speed of, say, 6 cm/s, then after three hours, a particle will have travelled about 650 m, corresponding to a nondimensional distance $\hat{x} = x/L = 13$. From 2.22, it is clear that the far-field concentration estimate is always smaller than that which would be computed using the near-field formula. To be conservative, then, we choose $\hat{x}_M$ (which must be between 650 m and 4 km) to be equal to 650 m, so that concentrations at intermediate distances from the platform will be overpredicted.

Trajectory

During the time in which the pollutant plume is being diluted, it is swept downstream in a continuously changing current. Thus at each time step, the pollutant is advected in different directions over different incremental distances. The model keeps track of this trajectory, and thereby identifies different impact areas which might be affected.

To calculate subsurface pollutant trajectories, the model requires measured (or assumed) values of the speed and direction of subsurface currents (e.g., at 10 m depth), at each time step. If V is the speed and θ the bearing of the subsurface current, then the eastward (Δx_i) and northward (Δy_i) displacements during the ith time interval Δt are given by

$$\Delta x_i = V_i \, \Delta t \, \sin\theta_i \qquad 2.23$$

$$\Delta y_i = V_i \, \Delta t \, \cos\theta_i \qquad 2.24$$

The model expresses these displacements as incremental changes in the range ΔR, and bearing, Δϕ, of the pollutant during the ith time step:

$$\Delta R_i \equiv \left[(\Delta x_i)^2 + (\Delta y_i)^2\right]^{1/2} \qquad 2.25$$

$$\Delta \phi_i \equiv \tan^{-1}\left[\frac{\Delta x_i}{\Delta y_i}\right] \qquad 2.26$$

The position of the pollutant relative to the source is given by the net range and bearing:

$$R = \sum_i \Delta \overrightarrow{Ri} \equiv \left[\left[\sum_i \Delta x_i \right]^2 + \left[\sum_i \Delta y_i \right]^2 \right]^{1/2} \qquad 2.27$$

$$\phi = \tan^{-1} \left[\frac{\sum_i \Delta x_i}{\sum_i \Delta y_i} \right] \qquad 2.28$$

The values for incremental and net range and bearing are computed and printed at each time step.

2.3 Floating Pollutants

Subsurface currents are often different from surface currents so the trajectory of floating pollutants is calculated independently. The trajectory of the floating pollutants is tracked in the same manner as the trajectory of the vertically mixed pollutants. The essential difference enters in relating the observed wind to the surface drift current. Floating pollutants are subject to the direct action of the wind. They are carried along by the wind-driven surface currents, which do not penetrate throughout the depth of the water column. The direction of movement is assumed to be directly with the wind. The task is to describe the trajectory of a mass of floating pollutants as the wind changes speed and direction over time.

The procedure sequence used in the model to calculate floating pollutant trajectories is as follows:

- The size and number of time intervals for which the trajectory is to be computed are specified;
- The speed and direction of the wind at each time step is read in;
- The program then computes the corresponding drift current induced by the wind, displaces the mass of pollutant accordingly, and keeps track of the total movement of the pollutant mass.

Wind drift currents will attain a speed approximately 3.5% of the wind speed 10 m above the surface, provided the wind has been blowing long enough. If the wind changes speed or direction, some time must elapse before the drift current reaches its equilibrium value. The relationships among wind speed, drift currents, and wind duration have been described by James (1968), and relevant results are reproduced in Figure 1. (It is assumed here that wind duration, not fetch, will dominate the drift current. This assumption is reasonable for most of the observed winds in the western part of the Gulf of Mexico). The dotted line in Figure 1 denotes the time required for a given wind field to generate its equilibrium drift current, T_e. The program automatically keeps track of the wind duration - if it has been long enough, the equilibrium value of the drift current V_D is assigned, otherwise the drift velocity is reduced by the ratio of the observed duration, T_w to the equilibrium duration, T_e. Thus

$$V_D = 0.035\, V_w, \qquad T_w > T_e \qquad 2.29$$

$$V_D = 0.035\, V_w \frac{T_w}{T_e}, \qquad T_w \leq T_e \qquad 2.30$$

If the wind changes speed, the following method described by James is used. If the wind speed increases, the program computes the time it would take for the higher wind speed to generate the drift current existing at the time of the increase. This gives an "equivalent duration" period for the higher wind speed, and the computation then proceeds as before. If the wind speed decreases, it is assumed that the drift current immediately drops to the equilibrium value corresponding to the lower wind speed. Changes in wind direction are handled by treating the two orthogonal components of wind speed separately in the manner described above.

The initial discharge is assumed to be confined to within 1 meter of the surface. As in the case of vertically mixed pollutants, it is assumed that the initial mixing occurs in a volume equal to 1/8 of that occupied by the platform (to 1 m depth).

2.4 Settling Particles

The purpose of modeling the sediment settling velocities is to estimate how far from the source particles of various sizes will be carried by the current before they are deposited on the sea floor. The model assumes that the small sediment particles are simply carried along by the horizontal current while they are settling towards the bottom. The horizontal distance x_s, travelled by the sediments before settling to the bottom is

$$x_s = Ut_s \qquad 2.31$$

where t_s is the time required to settle to the bottom and U is the ambient current. The time t_s for settling is

$$t_s = \frac{D}{W_s} \qquad 2.32$$

where D is the water depth and W_s is the settling velocity.

The settling velocities for small particles follow Stoke's law,

$$W_s = \frac{gd^2}{18\nu} \ (\delta_s - \delta_w) \qquad 2.33$$

where g is the gravitational acceleration, ν is the kinematic viscosity of water, d is the diameter of the sediment particles, and δ_s and δ_w are the specific weights of the sediment and seawater, respectively. Taking $g = 981$ cm/s^2, $\nu = 1.31 \times 10^2$ cm^2/s (at 10°C), and representative values of $\delta_s = 2.65$ (sand, silt), and $\delta_w = 1.025$ (10°C, 33 0/00) we find

$$W_s \doteq 6.8 \times 10^3 \ d^2 \qquad 2.34$$

in cgs units. Table 1 lists settling velocities for various particle sizes. A particle of diameter 0.012 cm will have a settling velocity of 1 cm/s. For larger particles, the approximations upon which Equation 2.34 is based begin to break down.

The program is written so that if the user specifies ν, δ_s and δ_w, Equation 2.33 is used; otherwise, the default value incorporated in Equation 2.34 are used to compute settling velocities. Unless d is specified, the program computes w_s, t_s, and x_s for particle sizes from 0.001 to 0.015 cm diameter.

3. DESCRIPTION OF MODEL OUTPUT

3.1 Printed Output

The output of the model is shown in Figure 2. This output consists of some initial remarks and computations, calculations made at each time step, a summary table, and computations for the settling pollutants. The letters in the following discussion correspond to those shown in Figure 2.

The first set of variables written at (A) are some of the input parameters provided by the user. The names of the parameters are self-explanatory. The seasons are numbered consecutively with winter corresponding to 1.

The output at (B) consists of two parts which describe the initial mixing of the vertically distributed and floating pollutants as they are swept past the platform structure by the water currents. The "release advection time" is the time it takes the current (surface or subsurface) to be carried past the platform, computed according to Equation 2.1. During this time, the "mass (of pollutant) released" is computed according to Equation 2.2. The volume in which the pollutant is mixed is computed according to Equation 2.3. For the surface pollutants the depth d is set equal to 1 m in Equation 2.3. The initial concentration is then computed according to Equation 2.4.

The computations made in (C) through (F) are repeated for each step as long as input data are supplied. In (C) the time step number and elapsed time are written. In (D) the input subsurface current speed (UCUR) and direction (UDIR) and the wind speed (VWIND) and direction (VDIR) are written. The oceanographic convention of specifying the direction of a current as the direction towards which the current is going and the meteorological convention of specifying the direction of a wind as the direction from which it blows are followed. Directions are measured clockwise from true north.

At (E) the fate of the vertically mixed pollutants is described. The incremental changes in the range and bearing, "DEL RANGE" and "DEL BEAR" are computed according to Equations 2.23 through 2.26. The resulting position of the pollutant, relative to the source, is computed according to Equations 2.27 and 2.28 and written under the headings of

"RANGE" and "BEARING." If the range is small enough so that the pollutant is still in the near field the volume and radius over which the pollutant is mixed are computed according to Equation 2.7. If the pollutant is already in the far field, the width of the wake, computed according to Equation 2.11, is printed instead (see time step number 3 in Figure 2). Next the distance "x" travelled by the pollutant (that is, is the sum of all the range increments), is computed. This is the distance measure which is used to distinguish the near and far fields, and which is used to compute the width of the wake in Equation 2.11. Next, the nondimensional concentration "CHIND" is computed in the near field (according to Equation 2.9), and again in the far field (according to Equation 2.21). The dimensional concentration "CHI" is then obtained by multiplying the nondimensional concentration by the initial concentration which was computed at (B).

At (F) the fate of the floating pollutants is described. The drift current (computed according to Equations 2.29 and 2.30 for the eastward and northward components separately and then combined to give the drift current speed and direction) is printed first. Next, the incremental changes of range ("DEL RANGE") and bearing ("DEL BEAR") are computed according to Equations 2.23 through 2.26 (with V_i and D_i corresponding to the drift current just computed) and printed. Finally, the next position of the floating pollutants is written as "RANGE" and "BEARING" computed from Equations 2.27 and 2.28. The output at each time step, viz. (C) through (F) in Figure 2 is repeated for all input data.

After the computations at each time step are completed, a table summarizing some of the results is printed. This table includes the trajectory, concentration and width of the wake for the mixed pollutants and the trajectory for the floating pollutants. The format is self-explanatory and is shown at (G) in Figure 2. The purpose of the table is to aid in graphing results, and its use will be discussed below.

The fate of the sinking particles is described in the next section of output, which is shown at (H) in Figure 2. First, the values of water viscosity and the specific weights of the particles and of the water are written. Typical values for shelf water and sediments are assumed unless the user specifies otherwise. The settling velocities of particles in different size ranges are computed according to Equation 2.33, and the time it takes for a particle to settle to the bottom is computed according to Equation 2.32 using the water depth specified by the user. It is seen that different size particles remain suspended for varying amounts of time. To find out how far such particles have traveled and where they hit the bottom, the user must refer to results given in (F) at the time step corresponding to the settling time listed in (H). The suspended particle moves with the vertically mixed pollutants until it hits the bottom, and it therefore has the same trajectory until that time.

3.2 Graphical Output

A computer graphics software package has been used to generate graphs of the wake width, nondimensional concentrations as a function of time, and the range and trajectory of subsurface and floating pollutants. The "EZGRAPH" graphics package, developed by AVCO Computer Services was used for the initial model runs. These plotting routines are not particularly specialized, and any large computer facility is likely to have a plotting package to which the dispersion model can be conveniently coupled. The summary table at (G) in Figure 2 can be written onto a file in a format suitable for input to the plotting routine.

3.3 User's Manual

Running the Buccaneer Oil Field Dispersion Model is a straightforward procedure. The input data is in the form of two namelists defining the values of various parameters, followed by a sequence of cards which give the observed subsurface current and the wind speed at each time step. The order and format of input cards are illustrated in a sample input in Figure 3. To facilitate setting up the input data and making modifications to the program, Table 2 lists the name, units, and description of each input and output variable.

An annotated flow chart of the program is given in Figure 4 to indicate the calculation sequence. A separate list of subroutines along with their arguments (including a specification of which are inputs to and which are outputs from the subroutine) and a brief description of the function of each subroutine is given in Table 3. Finally, a complete listing of the program - the main program and all of the subroutines is given in Figure 5.

4. RESULTS AND DISCUSSION

4.1 Results of Sample Computer Runs

The dispersion model for the Buccaneer Oil Field was run using data for six two-day periods — three each in winter (February) and summer (August). Output results are summarized in five sets of graphs. The first set, Figures 6 through 11, shows the growth of the pollutant wake as vertically distributed pollutants are transported downstream from the platform. These graphs indicate that the wake can spread to approximately 1 km in width within 48 hours. No appreciable differences in the rate or extent of wake spreading are indicated between seasons.

Figures 12 through 17 show the decrease in pollutant concentration (non-dimensional) over time, for vertically distributed pollutants. Concentrations decrease by a factor of approximately 10^{-6} in 48 hours, as pollutants are dispersed downstream. Initial turbulent mixing reduces concentrations by 10^{-2} in the immediate vicinity of the platform, and the remainder of the dispersion occurs as currents carry the pollutants downstream. The overall patterns are similar for all cases examined. The graphs showing reduction of concentration over range (Figures 18 through 23) also indicate a regular rate of reduction, but the total distance transported varies more among the specific cases examined.

The trajectories of subsurface pollutants are illustrated in Figures 24 through 29. For ease of reference, these results are also summarized in composite graphs indicating the relationship to the coastline (Figures 30 and 31; these graphs are not output from the computer). The map figures demonstrate an expected variability in discrete trajectories for each sample date. However, it is also clearly evident that vertically mixed pollutants are transported over greater distances in the winter season than in the summer. The winter trajectories generally paralleled the coastline, and no short-term impact on the Texas coast is indicated.

Floating pollutant trajectories for the sample dates are presented in Figures 32 through 37, and summarized in Figures 38 and 39. Seasonal differences in trajectories are even more marked than those for vertically distributed pollutants. The floating pollutants are carried much greater distances by wind drift currents in February than in August. These results also indicate that the coast southwest of Galveston could be affected by floating pollutants within about two days in winter.

4.2 Discussion

Actual field measurements and monitoring programs are limited in the extent of data which can be obtained. The development of models allows for reduced data gathering, since only a relatively small number of data points are needed to verify model predictions. Specifically, the development of applicable hydrodynamic models is necessary to meet all of the objectives and goals of the study program in assessing the environmental impacts of an active oil and gas field in the northwestern Gulf of Mexico. These models are needed in order to project the extent of environmental alterations associated with the development of an active oil and gas field, to quantify their distribution in time and space in the marine ecosystem, and to be able to predict how these sources and their distribution will ultimately impinge upon and be absorbed by the system.

The dispersion model of the Buccaneer Oil Field provides a significant tool which can be used in conjunction with the results from other work units to evaluate the effects of operational contaminant discharges on the surrounding marine ecosystem. Preliminary results of the model indicate rapid dispersion, and long-range transport of minute quantities of pollutants. Limited data on seasonal differences in the patterns of dispersion and transport indicate both similarities and differences in these processes. Pollutants appear to be transported over substantially greater distances in winter than in summer.

Further analyses will need to be made, using data from a variety of seasons and weather conditions, to verify these patterns and expand the data base for prediction.

The model is designed for use with observed wind, currents, particle size inputs, etc. The source of these observations can be local measurements, weather service predictions, or any other sources of appropriate data.

Validation of the model results will also require correlation with measured pollutant distributions. The very low concentration of pollutants expected from this analysis poses some problems in the methodology for model verification. The measurements of pollutant distribution in the sediments can be used, at least in part, to assess the applicability of the model for sinking pollutants. For the other portions of the pollutant load -- surface and subsurface pollutants -- other approaches must be employed. High precision analytical methods could be used to determine pollutant dispersion for specific episodes, particularly in the near-field region. Other methods, such as quantitative radiotracer or dye tracer studies could also be employed to verify model predictions. Once the model is shown to be reliable and valid, it can be used to describe the distribution and extent of various parameters associated with the developed well site.

The efforts of this work unit form an integral part of the overall study program to evaluate the environmental effects of the BOF. An understanding of the physical dispersion and transport processes can be used to indicate the marine resource areas most likely to be impacted by BOF operations. Results of the modelling analyses can also be incorporated in a physical mass transport model to identify the pollutant input to various biological components of the ecosystem.

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APPENDIX A

TABLES

Table 1. Size Range and Settling Velocity for Fine Particles

	Particle Size	Settling Velocities w_s (cm/sec)		
Group Name	Range (Microns)	Lowest	Highest	Mean
Very fine sand	60-100	0.245	0.680	0.462
Coarse silt	20-60	$2.72\text{x}10^{-2}$	0.245	0.136
Medium silt	6-20	$2.45\text{x}10^{-3}$	$2.72\text{x}10^{-2}$	$1.43\text{x}10^{-2}$
Fine silt	2-6	$2.72\text{x}10^{-4}$	$2.45\text{x}10^{-3}$	$1.36\text{x}10^{-3}$
Clay	<2		$2.72\text{x}10^{-4}$	$0.68\text{x}10^{-4}$

Table 2. List of Input and Output Variables

Name	Units	Description
Q	kgm s^{-1}	source strength
IS	(integer)	season number (winter = 1, spring = 2, ...)
RL	m	width of platform
DELT	hr	time step
ID	(integer)	date
DIAM	m	diameter of sediment particles
VISCOS	$m^2 s^{-1}$	viscosity of water near platform
WTSED	non-dimensional	the specific weight of the sinking pollutant
WTWAT	non-dimensional	specific weight of water near platform
UCUR	cm s^{-1}	speed of subsurface current
UDIR	degrees	direction (from true north) towards which current flows
VWIND	ms^{-1}	speed of wind
VDIR	degrees	direction (from true north) from which wind blows
D	m	water depth
TI	min	release advection time
CHI1	kgm m^{-3}	initial concentration
VOL1	m^3	initial mixing volume
RM	kgm	mass released during TI
VDRIFT	cm s^{-1}	drift current
NSTEP		time step number
TIME	hr	elapsed time
DELRAN	km	change in range
RANGE	km	distance from source
BEAR	degrees	direction of pollutant
X	km	distance travelled
WAKWID	km	width of wake (far field only)
VOL	m^3	mixing volume (near field only)
R	m	radius (near field only)
CHIND	non-dimensional	non-dimensional concentration

Table 2 (Continued)

Name	Units	Description
DRFT	degrees	direction towards which drift current flows
TS	hr	settling time
WS	cm s^{-1}	settling velocity

Intermediate Variables

Name	Units	Description
U	cm s^{-1}	same as UCUR
T	hr	same as TIME
V	cm s^{-1}	same as VDRIFT
VL	cm s^{-1}	previous hours drift current (saved by subroutine UPDATE)
SUMX	km	cumulative distance travelled in x component of trajectory
SUMY	km	cumulative distance travelled in y component of trajectory
DELBR	degrees	change in bearing over previous hour

Table 3. List of Subroutines*

Name	Function
SOURCE (Q,U,RL,D,RM,TI,CHI1,VOL1)	Computes initial concentration of vertically distributed pollutants
NEAR (IS,T,VOL1,R,VOL,CHIND)	Computes the near field concentration of vertically distributed pollutants
SURF (RL,Q,V,TI,RM,VOL1,CHI1)	Computes initial concentration of surface (i.e., floating) pollutants
SETTLE (D,DIAM,VISCOS, WTSED, WTWAT,TS,WS)	Computes and writes settling velocities and settling times of various size particles
UPDATE (VW,VL,DELT,V)	Computes wind-induced drift current
TRAJEC (VX,VY,DELT,SUMX,SUMY, DELRAN,DELBR,RANGE,BEAR)	Computes trajectory of vertically distributed or floating pollutants

*Variables which are underlined in the argument list are output from the subroutine.

APPENDIX B

FIGURES

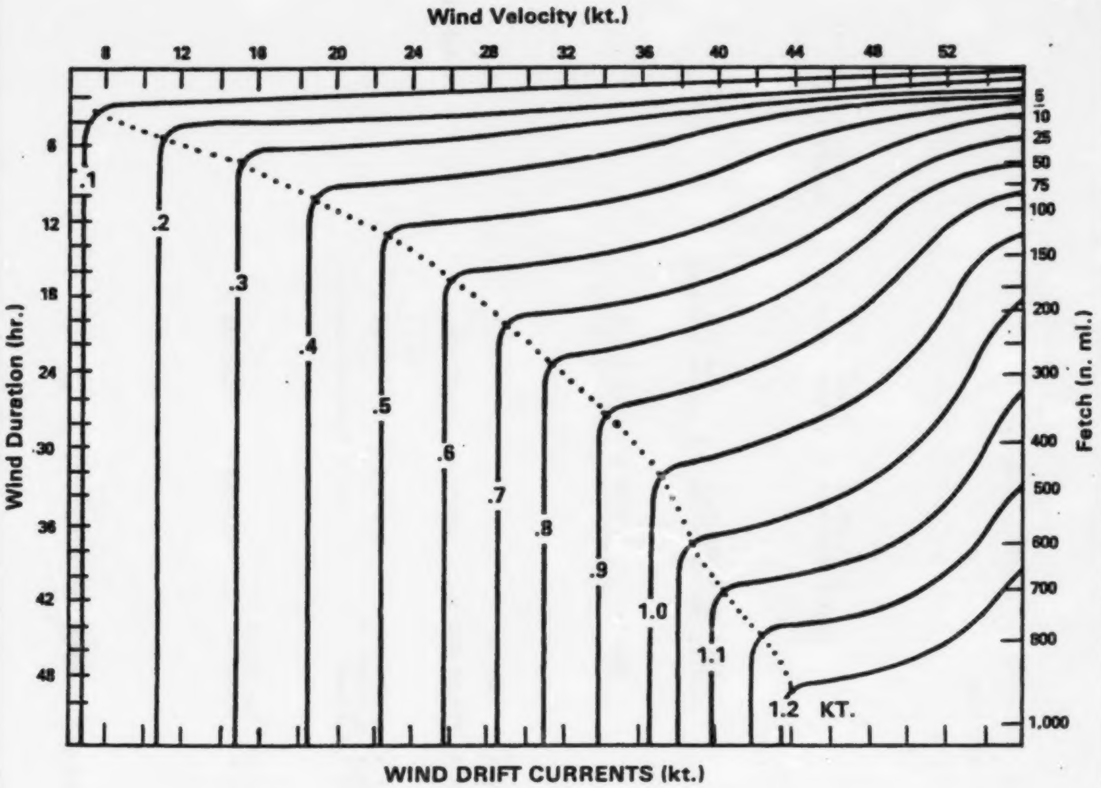
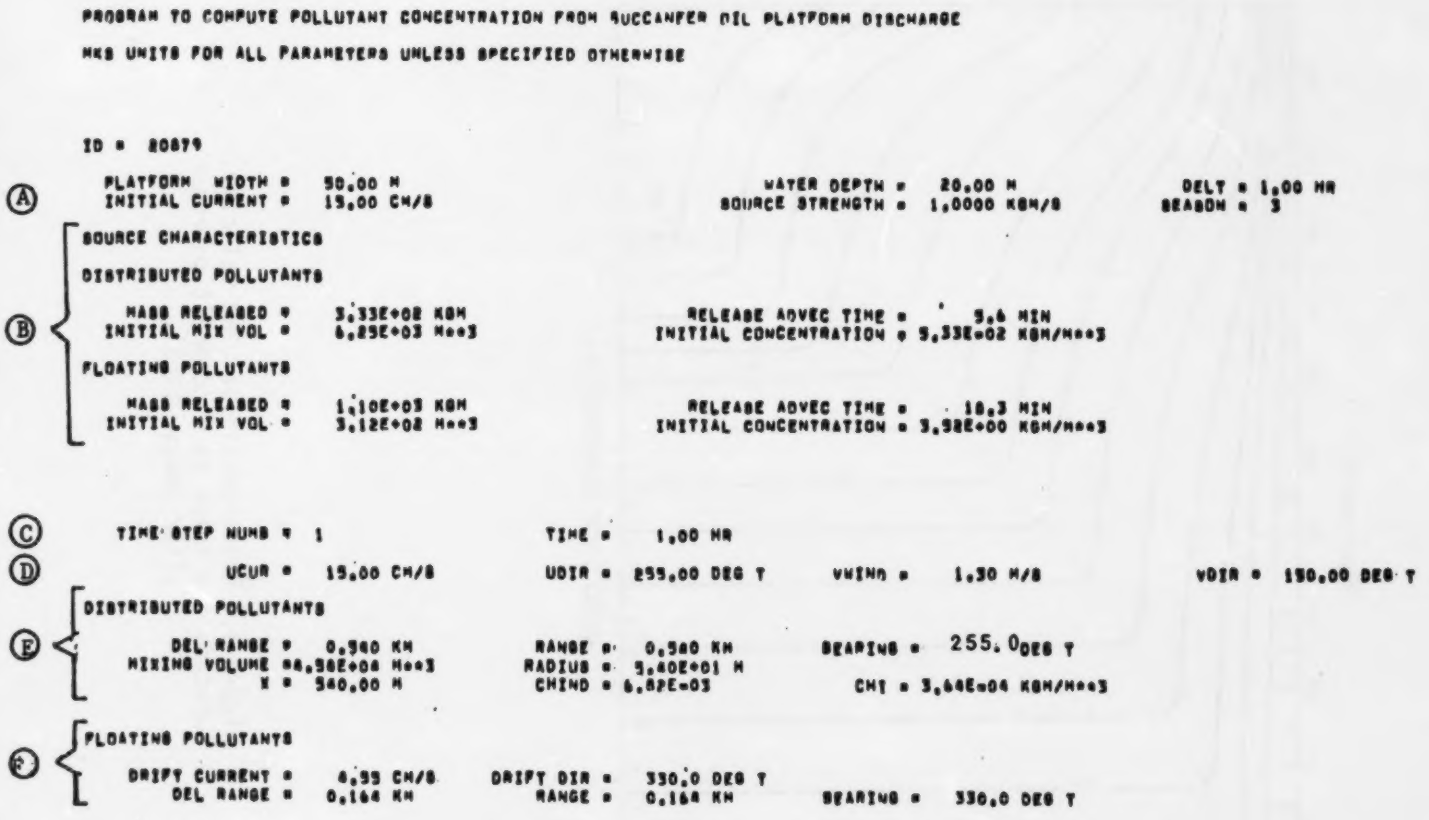


Figure 1. Relationship of wind velocity, duration and fetch to wind drift currents (after James, 1968).



```
PROGRAM TO COMPUTE POLLUTANT CONCENTRATION FROM BUCCANEER OIL PLATFORM DISCHARGE

MKS UNITS FOR ALL PARAMETERS UNLESS SPECIFIED OTHERWISE


ID =  20879

     PLATFORM  WIDTH =   50.00 M                        WATER DEPTH =   20.00 M            DELT = 1.00 HR
 Ⓐ   INITIAL CURRENT =   15.00 CM/S                 SOURCE STRENGTH =  1.0000 KGM/S        SEASON =  3

   SOURCE CHARACTERISTICS

   DISTRIBUTED POLLUTANTS

       MASS RELEASED =    3.33E+02 KGM               RELEASE ADVEC TIME =      5.6 MIN
 Ⓑ   INITIAL MIX VOL =    6.25E+03 M**3          INITIAL CONCENTRATION = 5.33E-02 KGM/M**3

   FLOATING POLLUTANTS

       MASS RELEASED =    1.10E+03 KGM               RELEASE ADVEC TIME =     18.3 MIN
     INITIAL MIX VOL =    3.12E+02 M**3          INITIAL CONCENTRATION = 3.52E+00 KGM/M**3


 Ⓒ    TIME STEP NUMB =  1                  TIME =    1.00 HR
 Ⓓ             UCUR =   15.00 CM/S         UDIR =  255.00 DEG T      VWIND =    1.30 M/S            VDIR =  150.00 DEG T
   DISTRIBUTED POLLUTANTS

 Ⓔ        DEL RANGE =   0.540 KM          RANGE =   0.540 KM        BEARING =  255.0 DEG T
      MIXING VOLUME =4.58E+04 M**3       RADIUS =  5.40E+01 M
                  X =  540.00 M           CHIND = 6.87E-03             CHI = 3.64E-04 KGM/M**3

   FLOATING POLLUTANTS

 Ⓕ    DRIFT CURRENT =    4.55 CM/S    DRIFT DIR =   330.0 DEG T
          DEL RANGE =   0.164 KM          RANGE =   0.164 KM        BEARING =   330.0 DEG T
```

Figure 2. Example output of computer program.

```
   TIME STEP NUMB =  2                  TIME =    2.00 HR

           UCUR =   14.00 CM/S          UDIR =  269.00 DEG T      VWIND =    1.30 M/S            VDIR =  150.00 DEG T
DISTRIBUTED POLLUTANTS

      DEL RANGE =   0.504 KM            RANGE =   1.036 KM        BEARING =  261.8 DEG T
  WIDTH OF WAKE =   0.162 KM
              X = 1084.00 M             CHIND = 1.35E-03               CHI = 7.18E-05 KGM/M**3

FLOATING POLLUTANTS

  DRIFT CURRENT =    4.55 CM/S      DRIFT DIR =   330.0 DEG T
      DEL RANGE =  0.164 KM             RANGE =   0.328 KM        BEARING =   330.0 DEG T


   TIME STEP NUMB =  3                  TIME =    3.00 HR

           UCUR =   14.00 CM/S          UDIR =  272.00 DEG T      VWIND =    1.30 M/S            VDIR =  150.00 DEG T
DISTRIBUTED POLLUTANTS

      DEL RANGE =   0.504 KM            RANGE =   1.555 KM        BEARING =  265.1 DEG T
  WIDTH OF WAKE =   0.197 KM
              X = 1548.00 M             CHIND = 4.91E-04               CHI = 2.62E-05 KGM/M**3

FLOATING POLLUTANTS

  DRIFT CURRENT =    4.55 CM/S      DRIFT DIR =   330.0 DEG T
      DEL RANGE =  0.164 KM             RANGE =   0.491 KM        BEARING =   330.0 DEG T
```

(Repeat time steps as long as input data are supplied)

Figure 2 (Continued)

```
Ⓖ SUMMARY TABLE
    TIME (HR)    X MIXED (KM)  Y MIXED (KM)  RANGE.MIX (KM) CONCEN ND     WAKE (KM)     X FLOAT (KM)  Y FLOAT (KM)  RANGE FL (KM)

    1.000E+00    -5.216E-01    -1.398E-01     5.400E-01     6.822E-03     1.162E-01    -8.190E-02     1.419E-01     1.638E-01
    2.000E+00    -1.026E+00    -1.406E-01     1.036E+00     1.346E-03     1.616E-01    -1.638E-01     2.837E-01     3.276E-01
    3.000E+00    -1.529E+00    -1.310E-01     1.535E+00     4.912E-04     1.967E-01    -2.457E-01     4.256E-01     4.914E-01
    4.000E+00    -2.029E+00    -1.924E-01     2.039E+00     2.400E-04     2.265E-01    -3.935E-01     5.642E-01     6.878E-01
    5.000E+00    -2.475E+00    -4.778E-02     2.479E+00     1.386E-04     2.510E-01    -5.899E-01     6.776E-01     8.984E-01
    6.000E+00    -2.894E+00     5.673E-02     2.894E+00     8.893E-05     2.717E-01    -7.863E-01     7.608E-01     1.094E+00
    7.000E+00    -3.325E+00     7.934E-02     3.326E+00     6.102E-05     2.909E-01    -9.827E-01     8.140E-01     1.276E+00
    8.000E+00    -3.792E+00     1.038E-01     3.794E+00     4.379E-05     3.103E-01    -1.250E+00     8.485E-01     1.511E+00
    9.000E+00    -4.219E+00     3.625E-02     4.219E+00     3.281E-05     3.273E-01    -1.550E+00     8.140E-01     1.751E+00
    1.000E+01    -4.684E+00    -2.079E-02     4.684E+00     2.523E-05     3.447E-01    -1.746E+00     7.695E-01     1.900E+00
    1.100E+01    -5.111E+00    -8.091E-02     5.112E+00     1.997E-05     3.600E-01    -2.023E+00     6.387E-01     2.122E+00
    1.200E+01    -5.540E+00    -1.336E-01     5.542E+00     1.612E-05     3.747E-01    -2.419E+00     4.818E-01     2.467E+00
    1.300E+01    -5.849E+00     5.185E-02     5.849E+00     1.331E-05     3.865E-01    -2.948E+00     2.700E-01     2.961E+00
    1.400E+01    -6.109E+00     3.969E-01     6.122E+00     1.109E-05     4.002E-01    -3.375E+00     1.149E-01     3.376E+00
    1.500E+01    -6.276E+00     6.746E-01     6.312E+00     9.422E-06     4.102E-01    -3.848E+00    -5.750E-02     3.849E+00
    1.600E+01    -6.443E+00     1.033E+00     6.525E+00     8.048E-06     4.221E-01    -4.335E+00    -1.879E-01     4.339E+00
    1.700E+01    -6.575E+00     1.329E+00     6.708E+00     6.972E-06     4.316E-01    -4.900E+00    -1.305E-01     4.902E+00
    1.800E+01    -6.625E+00     1.686E+00     6.836E+00     6.074E-06     4.419E-01    -5.391E+00    -1.146E-02     5.391E+00
    1.900E+01    -6.796E+00     1.742E+00     7.016E+00     5.390E-06     4.470E-01    -5.685E+00     1.506E-01     5.688E+00
    2.000E+01    -7.168E+00     1.606E+00     7.346E+00     4.748E-06     4.579E-01    -5.767E+00     3.005E-01     5.775E+00
    2.100E+01    -7.669E+00     1.553E+00     7.825E+00     4.183E-06     4.715E-01    -5.849E+00     4.624E-01     5.866E+00
    2.200E+01    -8.151E+00     1.406E+00     8.272E+00     3.708E-06     4.847E-01    -5.931E+00     5.842E-01     5.960E+00
    2.300E+01    -8.651E+00     1.336E+00     8.753E+00     3.305E-06     4.975E-01    -5.988E+00     6.824E-01     6.027E+00
    2.400E+01    -9.257E+00     1.251E+00     9.341E+00     2.945E-06     5.126E-01    -6.066E+00     8.188E-01     6.121E+00
    2.500E+01    -9.882E+00     1.083E+00     9.942E+00     2.634E-06     5.282E-01    -6.066E+00     1.017E+00     6.151E+00
    2.600E+01    -1.057E+01     1.107E+00     1.062E+01     2.364E-06     5.441E-01    -6.066E+00     1.181E+00     6.180E+00
    2.700E+01    -1.122E+01     1.295E+00     1.130E+01     2.132E-06     5.596E-01    -6.063E+00     1.294E+00     6.200E+00
    2.800E+01    -1.183E+01     1.688E+00     1.195E+01     1.928E-06     5.755E-01    -6.047E+00     1.448E+00     6.218E+00
    2.900E+01    -1.223E+01     2.048E+00     1.240E+01     1.761E-06     5.871E-01    -6.004E+00     1.391E+00     6.163E+00
    3.000E+01    -1.246E+01     2.491E+00     1.271E+01     1.617E-06     5.977E-01    -6.032E+00     1.291E+00     6.169E+00
    3.100E+01    -1.270E+01     2.807E+00     1.301E+01     1.493E-06     6.060E-01    -6.098E+00     1.123E+00     6.201E+00
    3.200E+01    -1.302E+01     2.971E+00     1.336E+01     1.305E-06     6.133E-01    -6.233E+00     8.766E-01     6.294E+00
    3.300E+01    -1.341E+01     3.060E+00     1.375E+01     1.285E-06     6.214E-01    -6.448E+00     7.065E-01     6.486E+00
    3.400E+01    -1.383E+01     3.150E+00     1.419E+01     1.194E-06     6.300E-01    -6.767E+00     4.797E-01     6.784E+00
    3.500E+01    -1.430E+01     3.198E+00     1.465E+01     1.111E-06     6.392E-01    -7.123E+00     1.571E-01     7.125E+00
    3.600E+01    -1.469E+01     3.219E+00     1.504E+01     1.037E-06     6.469E-01    -7.524E+00    -2.438E-01     7.528E+00
    3.700E+01    -1.516E+01     3.260E+00     1.550E+01     9.686E-07     6.559E-01    -7.961E+00    -6.804E-01     7.990E+00
    3.800E+01    -1.559E+01     3.320E+00     1.594E+01     9.070E-07     6.641E-01    -8.317E+00    -1.037E+00     8.381E+00
    3.900E+01    -1.597E+01     3.429E+00     1.633E+01     8.519E-07     6.719E-01    -8.459E+00    -1.119E+00     8.533E+00
    4.000E+01    -1.624E+01     3.610E+00     1.663E+01     8.023E-07     6.775E-01    -8.601E+00    -1.201E+00     8.684E+00
    4.100E+01    -1.637E+01     3.824E+00     1.681E+01     7.585E-07     6.821E-01    -8.808E+00    -1.161E+00     8.880E+00
    4.200E+01    -1.656E+01     3.993E+00     1.703E+01     7.179E-07     6.867E-01    -8.917E+00    -1.068E+00     8.981E+00
    4.300E+01    -1.682E+01     4.101E+00     1.732E+01     6.798E-07     6.920E-01    -8.999E+00    -9.370E-01     9.048E+00
    4.400E+01    -1.714E+01     4.157E+00     1.764E+01     6.438E-07     6.978E-01    -9.081E+00    -7.951E-01     9.116E+00
    4.500E+01    -1.743E+01     4.102E+00     1.790E+01     6.110E-07     7.029E-01    -9.193E+00    -5.996E-01     9.213E+00
    4.600E+01    -1.780E+01     3.973E+00     1.824E+01     5.789E-07     7.099E-01    -9.193E+00    -3.006E-01     9.198E+00
    4.700E+01    -1.827E+01     3.801E+00     1.866E+01     5.478E-07     7.187E-01    -9.183E+00     1.138E-01     9.184E+00
    4.800E+01    -1.888E+01     3.873E+00     1.927E+01     5.176E-07     7.293E-01    -9.155E+00     4.988E-01     9.169E+00
```

Figure 2 (Continued)

```
(H) SUBROUTINE SETTLE

   DIAM=  1.00E-05 M        VISCOS=  1.31E-06 M**2/SEC    WTSED =    2.65     WTWAT =    1.02

    DIAMETER                SETTLING VELOCITY              SETTLING TIME
       M                          M/S                            HR

    1.00E-05                       6.76E-05                        82.18
    2.00E-05                       2.70E-04                        20.54
    3.00E-05                       6.08E-04                         9.13
    4.00E-05                       1.08E-03                         5.14
    5.00E-05                       1.69E-03                         3.29
    6.00E-05                       2.43E-03                         2.28
    7.00E-05                       3.31E-03                         1.68
    8.00E-05                       4.33E-03                         1.28
    9.00E-05                       5.48E-03                         1.01
    1.00E-04                       6.76E-03                         0.82
    1.10E-04                       8.18E-03                         0.68
    1.20E-04                       9.74E-03                         0.57
    1.30E-04                       1.14E-02                         0.49
    1.40E-04                       1.33E-02                         0.42
    1.50E-04                       1.52E-02                         0.37
```

Figure 2 (Continued)

```
//BUCCANER JOB (88206623008,ERT--,101,---,JBEERS,620---------,4610),XX,X
// MSGLEVEL=1,CLASS=B
// EXEC FTG1CLG,PARM='NOSOURCE,NOLIST,NOMAP'
//FORT.SYSIN DD DSN=ERT4610.P6623008.BUCCANER,DISP=OLD
//GO.FT02F001 DD DSN=ERT4610.P6623008.DDDAY8,DISP=OLD
//GO.FT05F001 DD *
 &INPUT1 Q=1.,IS=3,RL=50.,D=20.,DELT=1.,
 ID=080878
 NMAX=48,
 &END
 &INPUT2 DIAM=0.,VISCOS=0.,WTSED=0.,WTWAT=0.,&END
15.        255.       1.3        150.
14.        269.       1.3        150.
14.        272.       1.3        150.
14.        263.       2.2        120.
13.        288.       1.8        120.
12.        284.       1.8         60.
12.        273.       1.8         60.
13.        273.       2.2         75.
12.        261.       3.1         50.
13.        263.       1.8         60.
12.        262.       2.7         60.
12.        263.       4.0         70.
10.        301.       4.9         70.
12.        323.       3.6         70.
 9.        329.       4.0         70.
11.        335.       4.0         75.
 9.        336.       4.5         95.
10.        352.       4.5        120.
 5.        288.       2.7        120.
11.        250.       1.3        150.
```

Figure 3. Order and format of input cards to computer program.

```
     14.        264.       1.3       150.
     14.        253.       1.3       150.
     14.        262.       0.9       150.
     17.        262.       1.3       150.
     18.        255.       1.8       180.
     19.        272.       1.3       180.
     19.        286.       0.9       185.
     20.        303.       1.3       200.
     15.        311.       0.9       300.
     14.        333.       1.3        10.
     11.        323.       2.2        30.
     10.        297.       3.1        40.
     11.        283.       2.7        60.
     12.        282.       3.6        60.
     13.        276.       4.0        45.
     11.        273.       4.5        45.
     13.        275.       4.9        45.
     12.        278.       4.0        45.
     11.        286.       1.3        60.
      9.        304.       1.3        60.
      7.        328.       1.8       100.
      7.        312.       1.8       150.
      8.        292.       1.3       150.
      9.        280.       1.3       150.
      8.        259.       1.8       150.
     11.        251.       3.1       180.
     14.        250.       3.6       185.
     17.        277.       3.1       190.
```

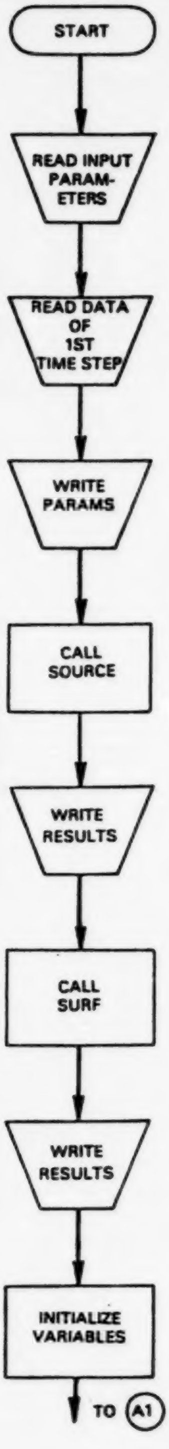
Figure 3 (Continued)

```
//GO.FT13F001 DD *
A TITLE1 15
  $
A TITLE2 15
A TITLE3 15
  $
A TITLE4 15
  $
A XLABEL 15
(T)IME (()HOURS())$
A YLABEL 15
(W)AKE (W)IDTH (()KM())$
 CHART 3 NTITLE 4 XSCALE 2 YSCALE 2
 XMIN 1. XMAX 100. YMIN .01 YMAX 10.
 XDATA
 YDATA
1
A YLABEL 15
(N)ON-(D)IMENSIONAL (C)ONCENTRATIONS$
 YMIN 1.E-7 YMAX 0.1 XMIN 1. XMAX 100.
 YDATA
1
A XLABEL 15
(R)ANGE (()KM())$
 XMIN .1 XMAX 100. YMIN 1.E-7 YMAX 0.1
 XDATA
1
A TITLE4 15
(S)UB-SURFACE (P)OLLUTANT (T)RAJECTORY$
A XLABEL 15
(X) (()KM())$
A YLABEL 15
(Y) (()KM())$
 XSCALE 1 YSCALE 1 NLINE 1
 XMIN -60. XMAX 60. YMIN -60. YMAX 60.
```

Figure 3 (Continued)

```
 XDATA
 YDATA
1
A TITLE4 15
(F)LDATING (P)OLLUTANT (T)RAJECTORYS
 XMIN -60, XMAX 60. YMIN -60. YMAX 60,
 XDATA
 YDATA
1
END
```

Figure 3 (Continued)


START
READ INPUT PARAM-ETERS
READ DATA OF 1ST TIME STEP
WRITE PARAMS
CALL SOURCE
WRITE RESULTS
CALL SURF
WRITE RESULTS
INITIALIZE VARIABLES
TO Ⓐ1

NAMELIST/INPUT 1/
Q, IS, RL, D, DELT, ID
NAMELIST/INPUT 2/DIAM, VISCOS, WTSED, WTWAT

UCUR, UDIR, VWIND, VDIR

Writes Ⓐ of Figure 2

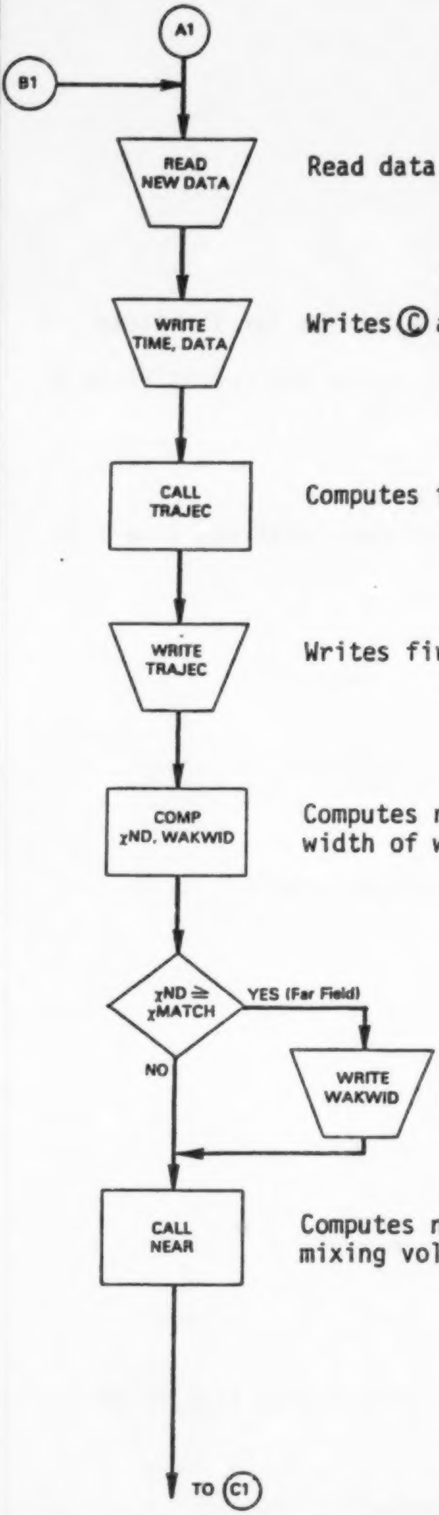
Computes initial mixing of vertically distributed pollutants

Writes first part of Ⓑ, Figure 2

Computes initial mixing of floating pollutants

Writes second part of Ⓑ, Figure 2

Figure 4. Annotated flow chart of computer program.


A1
B1
READ NEW DATA
WRITE TIME, DATA
CALL TRAJEC
WRITE TRAJEC
COMP χND, WAKWID
χND ≥ χMATCH
YES (Far Field)
NO
WRITE WAKWID
CALL NEAR
TO C1

Read data for new time step

Writes Ⓒ and Ⓓ of Figure 2

Computes trajectory for mixed pollutants

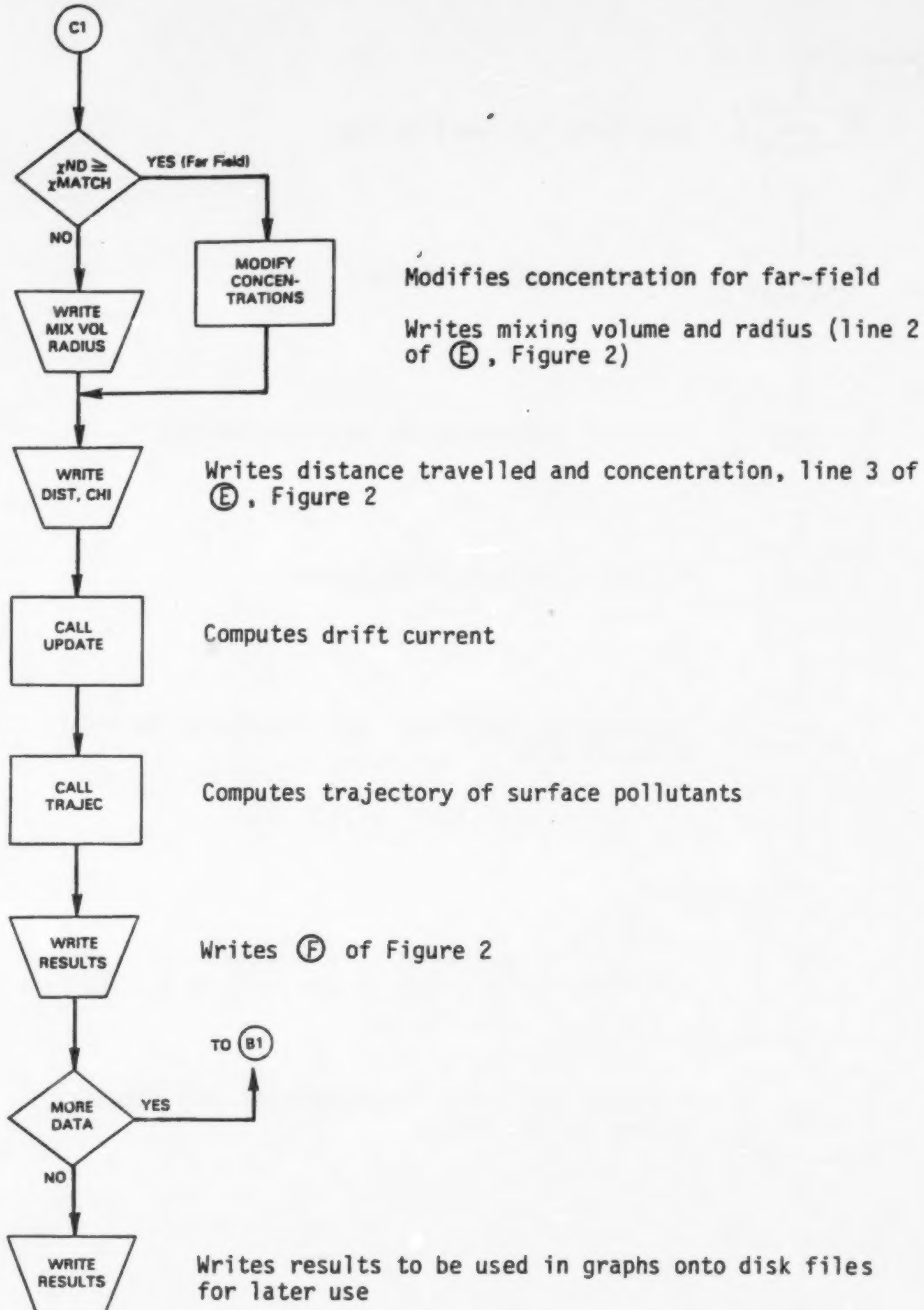
Writes first line of Ⓔ, Figure 2

Computes nondimensional distance travelled and width of wake

If pollutant is in the far-field regime, writes width of wake in line 2 of Ⓔ, Figure 2

Computes near-field nondimensional concentration mixing volume, radius

Figure 4 (Continued)


C1
χND ≥ χMATCH
YES (Far Field)
NO
MODIFY CONCEN-TRATIONS
WRITE MIX VOL RADIUS
WRITE DIST, CHI
CALL UPDATE
CALL TRAJEC
WRITE RESULTS
TO B1
MORE DATA
YES
NO
WRITE RESULTS
TO D1

Modifies concentration for far-field

Writes mixing volume and radius (line 2 of Ⓔ, Figure 2)

Writes distance travelled and concentration, line 3 of Ⓔ, Figure 2

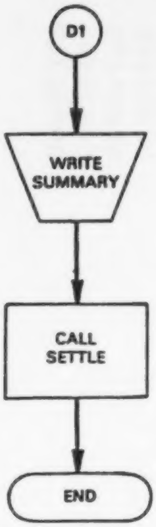
Computes drift current

Computes trajectory of surface pollutants

Writes Ⓕ of Figure 2

Writes results to be used in graphs onto disk files for later use

Figure 4 (Continued)


D1
WRITE SUMMARY
CALL SETTLE
END

Writes a table summarizing results to be used in graphs, Ⓖ of Figure 2

Computes settling velocities and times and writes Ⓗ of Figure 2

Figure 4 (Continued)

```
C***MAIN PROGRAM***
      NAMELIST/INPUT1/Q,IS,RL,D,DELT,ID,NMAX
      NAMELIST/INPUT2/DIAM,VISCOB,WTSED,WTWAT
      DIMENSION XF(50),YF(50),XM(50),YM(50),CONCND(50),TTIME(50),
     >RANGEM(50),WAKE(50),RANGEF(50)
      DATA XF,YF,XM,YM,CONCND,TTIME,RANGEM,WAKE,RANGEF/450*0./
      READ(5,INPUT1)
      READ(5,INPUT2)
      WRITE(6,14)
      WRITE(6,1)
C
C SPECIFY SOURCE AND CURRENT
C
      READ(5,21) UCUR,UDIR,VWIND,VDIR
      UCUR=UCUR/100.
      WRITE(6,2) ID,RL,D,DELT,UCUR,Q,IS
      DELT=DELT*3600.
      CALL SOURCE(Q,UCUR,RL,D,RM,T1,CHI1,VOL1)
      T1=T1/60.
      WRITE(6,12) RM,T1,VOL1,CHI1
      T1=T1*60.
      HOLD=CHI1
      VDRIFT=0.035*VWIND
      CALL SURF(RL,Q,VDRIFT,T1,RM,VOL1,CHI1)
      T1=T1/60.
      WRITE(6,12) RM,T1,VOL1,CHI1
      T1=T1*60.
      CHI1=HOLD
C
C CONCENTRATION IN THE WATER COLUMN
C
```

Figure 5. Complete computer program listing for the BOF platform dispersion model

```
      TIME=0.
      NSTEP=0
      SUMX=0.
      SUMY=0.
      X=0.
      SUMX1=0.
      SUMY1=0.
      X1=0.
      VWLX=-VWIND*SIN(VDIR/57.2958)
      VWLY=-VWIND*COS(VDIR/57.2958)
      VLX=0.035*VWLX
      VLY=0.035*VWLY
  140 NSTEP=NSTEP+1
      TIME=TIME+DELT
      IF(NSTEP .GT. 1) READ (5,21, END=9997) UCUR,UDIR,VWIND,VDIR
      IF(NSTEP.NE.1)UCUR=UCUR/100.


      TIME=TIME/3600.
      TTIME(NSTEP)=TIME
      WRITE(6,11) NSTEP,TIME
      TIME=TIME*3600.
      WRITE(6,22) UCUR,UDIR,VWIND,VDIR
      UXCUR=UCUR*SIN(UDIR/57.2958)
      UYCUR=UCUR*COS(UDIR/57.2958)
      CALL TRAJEC(UXCUR,UYCUR,DELT,SUMX,SUMY,DELRAN,DELBR,RANGE,BEAR)
      WRITE(6,19) DELRAN,RANGE,BEAR
      RANGEM(NSTEP)=RANGE/1000.
      XM(NSTEP)=SUMX/1000.
      YM(NSTEP)=SUMY/1000.
      X=X+DELRAN
      T=TIME
      XMATCH=13.
      XND= X/RL
      WAKWID=0.5*(2.*XND)**0.5
```

Figure 5 (Continued)

```
      WAKWID=WAKWID*RL
      WAKE(NSTEP)=WAKWID/1000.
      IF(XND .GE. XMATCH) WRITE(6,6) WAKWID
  100 CALL NEAR(IS,T,VOL1,R,VOL,CHIND)
      IF(XND .LT. XMATCH) WRITE(6,7) VOL,R
      IF(XND.GE.XMATCH)CHIND=CHIND*(XMATCH/XND)**0.5
  110 CHI= CHIND*CHI1
      CONCND(NSTEP)=CHIND
      WRITE(6,8)X,CHIND,CHI
C
C SEQUENTIAL TRAJECTORY ANALYSIS FOR SURFACE POLLUTANTS
C
      WDIR=VDIR
      VW=VWIND
      VWX=-VW*SIN(WDIR/57.2958)
      VWY=-VW*COS(WDIR/57.2958)
      WRITE(6,5)
      CALL UPDATE(VWX,VLX,DELT,VX)
      CALL UPDATE(VWY,VLY,DELT,VY)
      VDRIFT=(VX**2+VY**2)**0.5
      DRFT=ZTAN2(VX,VY)*57.2958
      IF(DRFT.LT.0.)DRFT=DRFT+360.
      WRITE(6,18) VDRIFT,DRFT
      CALL TRAJEC(VX,VY,DELT,SUMX1,SUMY1,DELRAN,DELBR,RANGE1,BEAR1)
      WRITE(6,19) DELRAN,RANGE1,BEAR1
      XF(NSTEP)=SUMX1/1000.
      YF(NSTEP)=SUMY1/1000.
      RANGEF(NSTEP)=RANGE1/1000.
      X1=X1+DELRAN
  120 CONTINUE
      GO TO 140
 9997 CONTINUE
      CALL GRAPHS(NMAX,TTIME,XM,YM,RANGEM,CONCND,WAKE,XF,YF,RANGEF,
     1ID)
      WRITE(6,14)
```

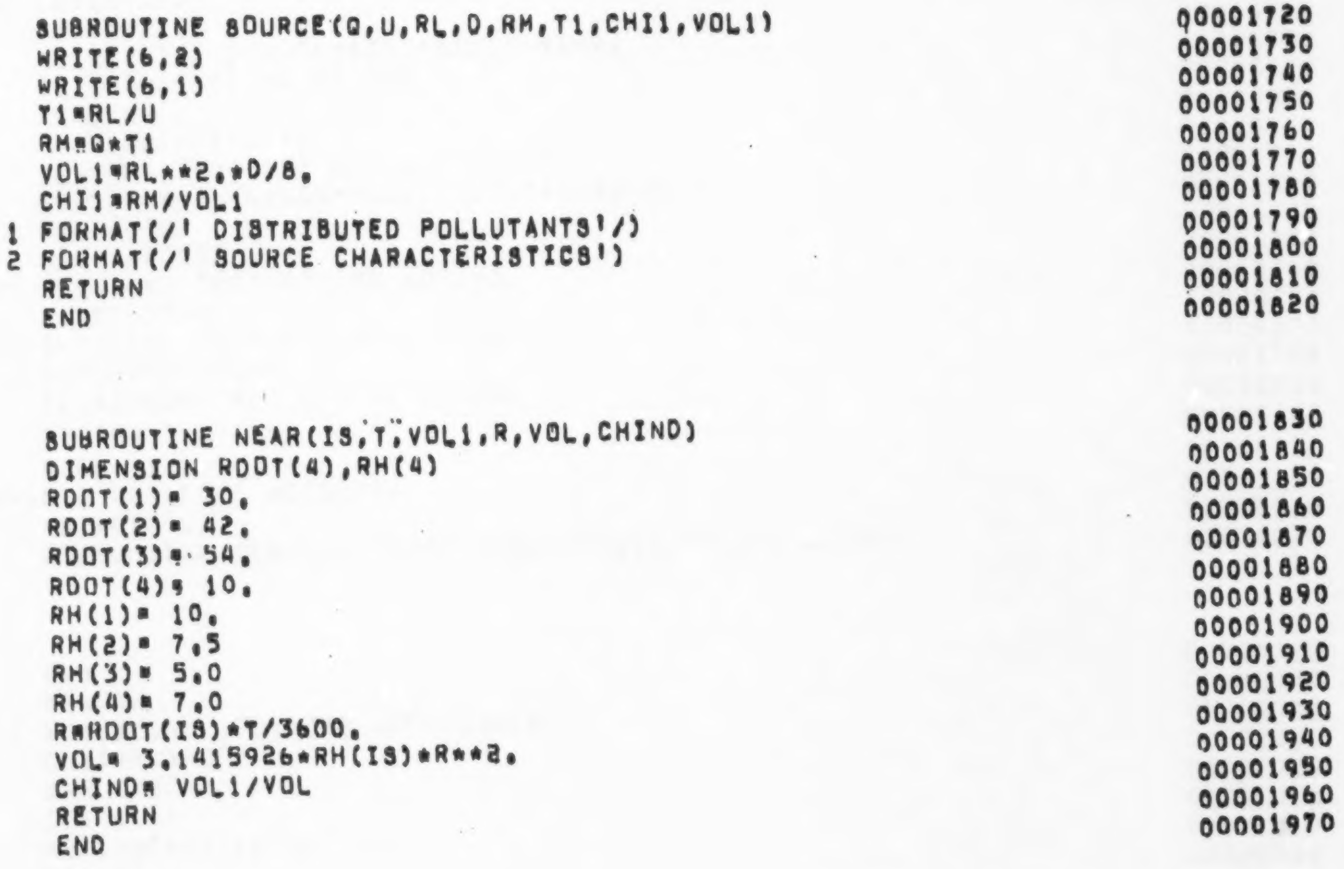
Figure 5 (Continued)

```
      WRITE(6,25)
      DO 150 I=1,NMAX
  150 WRITE(6,26) TTIME(I),XM(I),YM(I),RANGEM(I),CONCND(I),WAKE(I),
     @XF(I),YF(I),RANGEF(I)
C
C SETTLING PARTICLES
C
      CALL SETTLE(D,DIAM,VISCOS,WTSED,WTWAT,TS,WS)
C
    1 FORMAT(' PROGRAM TO COMPUTE POLLUTANT CONCENTRATION',
     @' FROM BUCCANEER OIL PLATFORM DISCHARGE'//' MKS UNITS FOR ALL ',
     &'PARAMETERS UNLESS SPECIFIED OTHERWISE'///)
    2 FORMAT(/' ID =',I7,/,
     >/,T3,' PLATFORM  WIDTH =',F8.2,' M',T64,'WATER DEPTH =',
     @F8.2,' M',T102,'DELT =',F5.2,' HR'/
     @T3,' INITIAL CURRENT =',+2PF8.2,' CM/S',T60,'SOURCE ',
     @'STRENGTH =',0PF8.4,' KGM/S',T100,'SEASON =',I3)
C   3 FORMAT(//,T7,'Q=',T10,F8.3,T30,'IS=',I4,
C    @T40,'TW=',T50,F8.1,T65,'RL =',F7.2,' M',T85,'D=',F7.2,' M',
C'   @T105,'DELT =',F7.2,' SEC')
    4 FORMAT(T19,' X=',T23,F10.2,' M',T55,'MEAN TRAVEL TIME =',
     @T73,F10.1,' S')
    5 FORMAT(//' FLOATING POLLUTANTS'/)
    6 FORMAT(T5,' WIDTH OF WAKE =',-3PF8.3,' KM')
    7 FORMAT(T5,' MIXING VOLUME =',1PE8.2,' M**3',T42,
     @'RADIUS =',1PE10.2,' M')
    8 FORMAT(T17,' X =',F8.2,' M',T43,
     @'CHIND =',1PE9.2,T72,'CHI =',1PE9.2,
     @' KGM/M**3')
C   9 FORMAT(/,T5,' PARTICLE DIAMETER=',T25,F10.5,' M',T54,'SETTLING ',
C    @'TIME=',T70,F10.2,' S',/,T5,' SETTLING VELOCITY=',T25,F10.5,
C    @' M/S',T50,'SETTLING DISTANCE=',T70,F10.2,' M')
   10 FORMAT(T10,' WIND SPEED=',T23,F10.2,' M/S',T59,'WIND ',
     @'DURATION=',T73,F10.2,' S',T95,'DRIFT CURRENT=',T110,F10.4,
     @' M/S')
```

Figure 5 (Continued)

```
   11 FORMAT(/////,T5,'TIME STEP NUMB =',I3,                              00001380
     *T44,'TIME =',F8.2,' HR')                                            00001390
   12 FORMAT(T5,' MASS RELEASED =',T25,1PE8.2,' KGM',T57,                 00001400
     *'RELEASE ADVEC TIME =',T78,0PF8.1,' MIN',                           00001410
     */,T3,' INITIAL MIX VOL =',T25,1PE8.2,' M**3',                       00001420
     *T54,'INITIAL CONCENTRATION =',T78,1PE8.2,' KGM/M**3')               00001430
   13 FORMAT(T5,' RELEASE ADVEC TIME =',T30,F8.1,' S',T50,                00001440
     *'DRIFT CURRENT =',T75,+2PF10.4,' CM/S')                             00001450
   14 FORMAT(1H1)                                                         00001460
C  15 FORMAT(I5,5X,F10.1)                                                 00001470
C  16 FORMAT(//////////T5,'TRAJECTORY COMPUTED FOR',I3,' TIME STEPS OF',00001480
C    *F8.1,' SEC EACH'/)                                                  00001490
C  17 FORMAT(2F10.1)                                                      00001500
   18 FORMAT(T5,' DRIFT CURRENT =',+2PF8.2,' CM/S',T39,'DRIFT DIR =',     00001510
     *0PF8.1,' DEG T')                                                    00001520
   19 FORMAT(T9,' DEL RANGE =',=3PF8.3,' KM',                             00001530
     *T43,'RANGE =',=3PF8.3,' KM',T69,'BEARING =',0PF8.1,                 00001540
     *' DEG T')                                                           00001550
C  20 FORMAT(4F10.1)                                                      00001560
   21 FORMAT(4F10.2)                                                      00001570
   22 FORMAT(/T15,'UCUR =',+2PF8.2,' CM/S',T44,'UDIR =',0PF8.2,' DEG T',00001580
     >T70,                                                                00001590
     >'VWIND =',F8.2,' M/S',T103,'VDIR =',F8.2,' DEG T'/,                 00001600
     >/,' DISTRIBUTED POLLUTANTS'/)                                       00001610
   23 FORMAT(T12,'SURF CUR =',F10.2,' M/S')                               00001620
   24 FORMAT(T7,' NET CURRENT =',+2PF8.2,' CM/S',T41,'NET DIR =',         00001630
     >0PF8.1,' DEG T')                                                    00001640
   25 FORMAT(' SUMMARY TABLE'/T6,'TIME (HR)',T19,'X MIXED (KM)',          00001650
     *T33,'Y MIXED (KM)',T47,'RANGE MIX (KM)',T62,'CONCEN ND',            00001660
     *T76,'WAKE (KM)',                                                    00001670
     *T89,'X FLOAT (KM)',T104,'Y FLOAT (KM)',T118,'RANGE FL (KM)'/)       00001680
   26 FORMAT( 1P9E14.3)                                                   00001690
      STOP                                                                00001700
      END                                                                 00001710
```

Figure 5 (Continued)



```
      SUBROUTINE SOURCE(Q,U,RL,D,RM,T1,CHI1,VOL1)
      WRITE(6,2)
      WRITE(6,1)
      T1=RL/U
      RM=Q*T1
      VOL1=RL**2.*D/8.
      CHI1=RM/VOL1
    1 FORMAT(/' DISTRIBUTED POLLUTANTS'/)
    2 FORMAT(/' SOURCE CHARACTERISTICS')
      RETURN
      END


      SUBROUTINE NEAR(IS,T,VOL1,R,VOL,CHIND)
      DIMENSION RDOT(4),RH(4)
      RDOT(1)= 30.
      RDOT(2)= 42.
      RDOT(3)= 54.
      RDOT(4)= 10.
      RH(1)= 10.
      RH(2)= 7.5
      RH(3)= 5.0
      RH(4)= 7.0
      R=RDOT(IS)*T/3600.
      VOL= 3.1415926*RH(IS)*R**2.
      CHIND= VOL1/VOL
      RETURN
      END
```

Figure 5 (Continued)

```
      SUBROUTINE SURF(RL,Q,V,T1,RM,VOL1,CHI1)
      WRITE(6,1)
      D1= 1.
      VOL1=RL**2.*D1/8.
      T1= RL/V
      RM= Q*RL/V
      CHI1=RM/VOL1
    1 FORMAT(/' FLOATING POLLUTANTS'/)
      RETURN
      END


      SUBROUTINE SETTLE(D,DIAM,VISCOS,WTSED,WTWAT,TS,WS)
      WRITE(6,3)
C COMPUTE SETTLING VELOCITY
      HOLD=DIAM
      DO 100 J=1,15
      IF(VISCOS .NE. 0.) GO TO 120
      VISCOS=1.31E-6
  120 IF(WTSED .NE. 0.) GO TO 130
      WTSED=2.65
  130 IF(WTWAT .NE. 0.) GO TO 140
      WTWAT=1.025
  140 GRAV=9.81
      CONST=GRAV*(WTSED-WTWAT)/(18.*VISCOS)
      IF(HOLD .EQ. 0.) DIAM=(1.E-5)*J
      WS=CONST*DIAM**2
      TS=D/WS
      IF(J .GT. 1) GO TO 150
      WRITE(6,4) DIAM,VISCOS,WTSED,WTWAT
      WRITE(6,1)
  150 TS=TS/3600.
      WRITE(6,2) DIAM,WS,TS
      TS=TS*3600.
```

Figure 5 (Continued)

```
                                                                                  00002300
      IF (HOLD·NE·O.) GO TO 110                                                   00002310
  100 CONTINUE                                                                    00002320
  110 CONTINUE                                                                    00002330
    1 FORMAT(T5,' DIAMETER',T30,'SETTLING VELOCITY',T60,                          00002340
     @'SETTLING TIME',/T10,'M',T38,                                               00002350
     @'M/S',T68,'HR',/)                                                           00002360
    2 FORMAT( T4,1PE10.2,T35,E10.2,T62,0PF10.2)                                   00002370
    3 FORMAT(///////////' SUBROUTINE SETTLE'/)                                    00002380
    4 FORMAT(T5,'DIAM=',1PE10.2,' M',T30,'VISCOS=',E10.2,' M**2/SEC',             00002390
     >T60,                                                                        00002400
     @'WTSED =',0PF8.2,T80,'WTWAT =',F8.2/)                                       00002410
      RETURN                                                                      00002420
      END


      SUBROUTINE UPDATE(VW,VL,DELT,V)                                             00002430
      SSV=0.035*VW                                                                00002440
      IF(ABS(VL) .GE. ABS(SSV))GO TO 100
      VWKT=ABS(VW)*1.9426                                                              000
      SSTMHR=4.05051-0.21258*VWKT+0.02770*VWKT**2                                 00002460
      SSTM=SSTMHR*3600.                                                           00002470
      DVDT=SSV/SSTM
      V=VL+DVDT*DELT                                                              00002510
      IF(ABS(V) .GT. ABS(SSV))GO TO 100
      GO TO 110                                                                   00002530
  100 V=SSV                                                                       00002540
  110 VL=V                                                                        00002553
      RETURN                                                                      00002560
      END                                                                         00002570
```

Figure 5 (Continued)

```
      SUBROUTINE TRAJEC(VX,VY,DELT,SUMX,SUMY,DELRAN,DELBR,RANGE,BEAR)   00002580
      DELX=VX*DELT                                                      00002590
      DELY=VY*DELT                                                      00002600
      SUMX=SUMX+DELX                                                    00002610
      SUMY=SUMY+DELY                                                    00002620
      DELRAN=(DELX**2+DELY**2)**0.5                                     00002630
      DELBR=ZTAN2(DELX,DELY)*57.2958                                     0000264
      IF(DELBR.LT.0.)DELBR=DELBR+360.                                   00002650
      RANGE=(SUMX**2+SUMY**2)**0.5                                      00002660
      BEAR= ZTAN 2 (SUMX, SUMY)*57.2958                                 00002670
      IF(BEAR.LT.0.)BEAR=BEAR+360.                                      00002680
      RETURN                                                            00002690
      END                                                               00002700


      SUBROUTINE GRAPHS(NMX,TTIME,XM,YM,RANGEM,CONCND,WAKE,XF,YF,RANGEF,00002710
     1ID)                                                               00002720
      DIMENSION TTIME(50),XM(50),YM(50),RANGEM(50),CONCND(50)           00002730
      DIMENSION WAKE(50),XF(50),YF(50),RANGEF(50)                       00002740
      REAL JACK/0./                                                     00002750
      INTEGER D(20,50)                                                  00002760
      READ(13,40) ((D(I,J),I=1,20),J=1,44)                              00002770
      NTOP=NMX+1                                                        00002780
      ID1=ID/10000                                                      00002781
      ID2=ID/100-ID1*100                                                00002782
      ID3=ID-ID1*10000-ID2*100                                          00002783
      WRITE(2,10) ((D(I,J),I=1,20),J=1,3)                               00002790
      WRITE(2,50) ID1,ID2,ID3                                           00002800
      WRITE(2,10) ((D(I,J),I=1,20),J=4,13)                              00002810
      WRITE(2,30) NMX                                                   00002820
      WRITE(2,10) (D(I,14),I=1,20)                                      00002830
      WRITE(2,20) (TTIME(N),N=1,NMX)                                    00002840
      WRITE(2,10) (D(I,15),I=1,20)                                      00002850
      WRITE(2,20) (WAKE(N),N=1,NMX)                                     00002860
```

Figure 5 (Continued)

```
      WRITE(2,10)  ((D(I,J),I=1,20),J=16,20)                   00002870
      WRITE(2,20)  (CONCND(N),N=1,NMX)                         00002880
      WRITE(2,10)  ((D(I,J),I=1,20),J=21,25)                   00002890
      WRITE(2,20)  (RANGEM(N),N=1,NMX)                         00002900
      WRITE(2,10)  ((D(I,J),I=1,20),J=26,34)                   00002910
      WRITE(2,30)  NTOP,NTOP                                   00002920
      WRITE(2,10)  (D(I,35),I=1,20)                            00002930
      WRITE(2,20)  JACK,(XM(N),N=1,NMX)                        00002940
      WRITE(2,10)  (D(I,36),I=1,20)                            00002950
      WRITE(2,20)  JACK,(YM(N),N=1,NMX)                        00002960
      WRITE(2,10)  ((D(I,J),I=1,20),J=37,41)                   00002970
      WRITE(2,20)  JACK,(XF(N),N=1,NMX)                        00002980
      WRITE(2,10)  (D(I,42),I=1,20)                            00002990
      WRITE(2,20)  JACK,(YF(N),N=1,NMX)                        00003000
      WRITE(2,10)  ((D(I,J),I=1,20),J=43,44)                   00003010
10    FORMAT(20A4)                                             00003020
20    FORMAT(1X,6E11.3)                                        00003030
30    FORMAT(' NDATA',1X,I2,1X,I2)                             00003040
40    FORMAT(20A4)                                             00003050
50    FORMAT(I2,'=',I2,'=',I2,'S')                             00003060
      RETURN                                                   00003070
      END                                                      00003080


      FUNCTION  ZTAN2 (X,Y)
      IF (X.NE.0..OR.Y.NE.0) GO TO 13
      ZTAN2=0.
      RETURN
13    ZTAN2=ATAN2 (X,Y)
      RETURN
      END
```

Figure 5 (Continued)

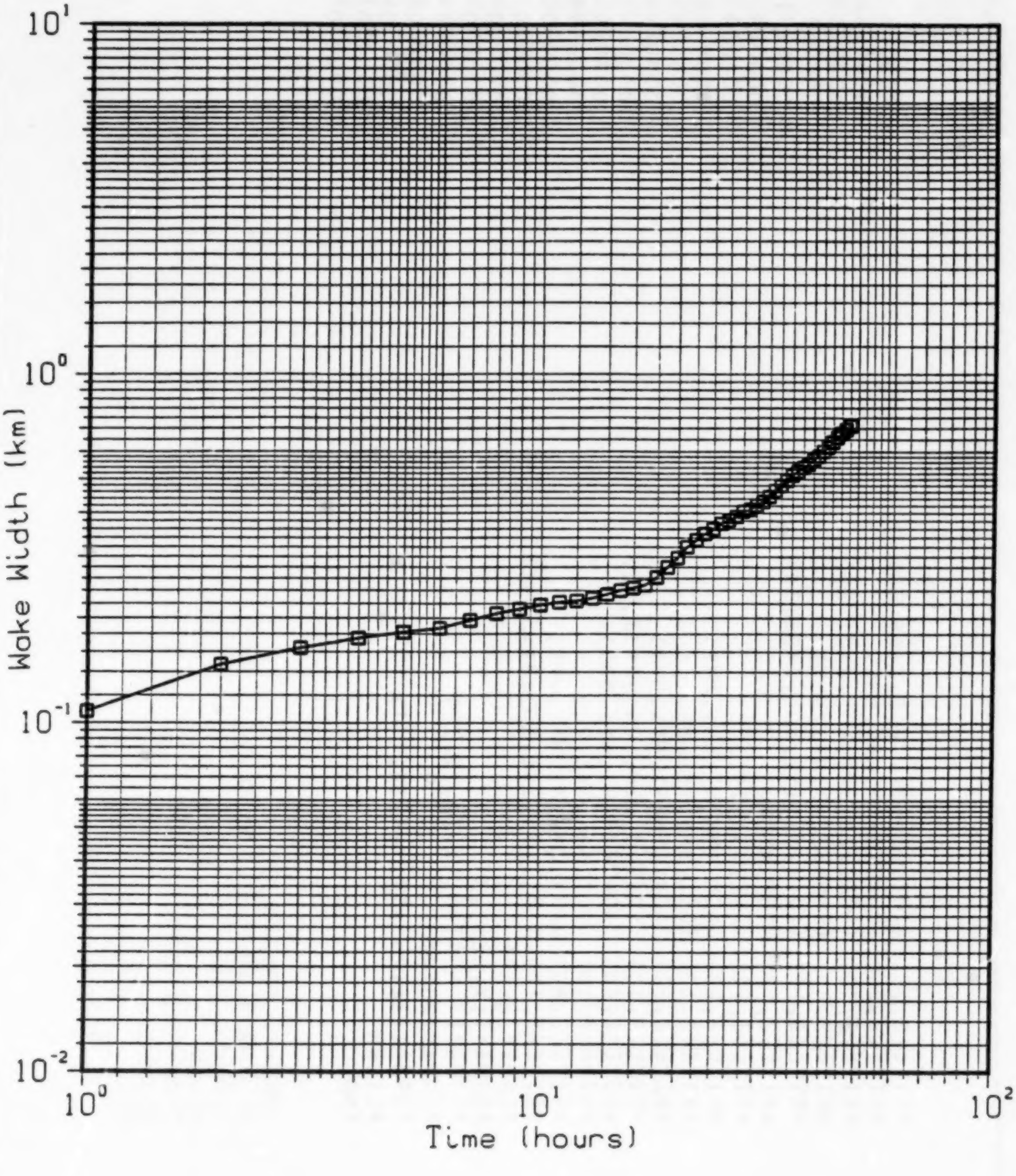


Figure 6. Growth of the pollutant wake downstream from the BOF platform, August 4, 1978

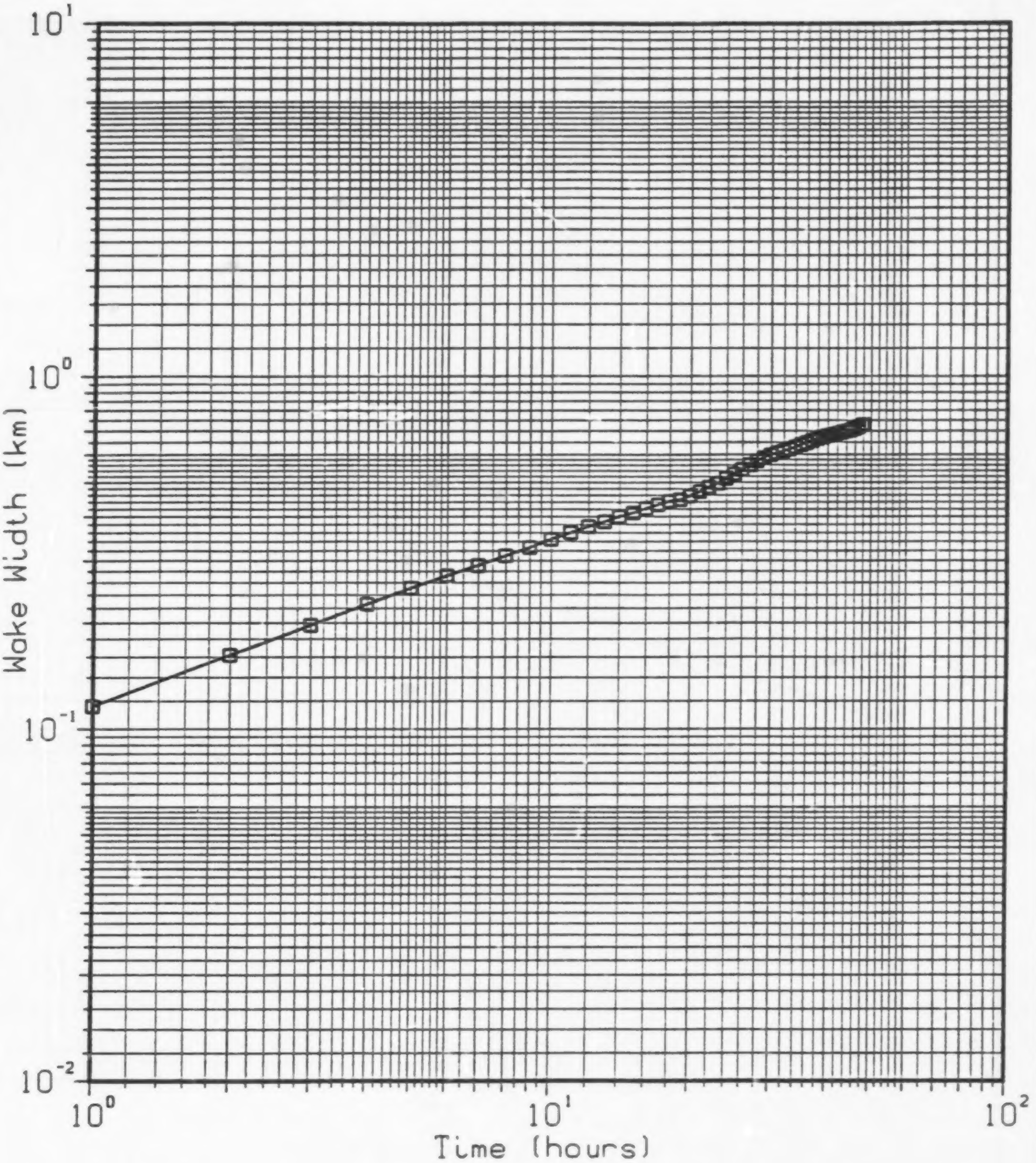


Figure 7. Growth of the pollutant wake downstream from the BOF platform, August 8, 1978

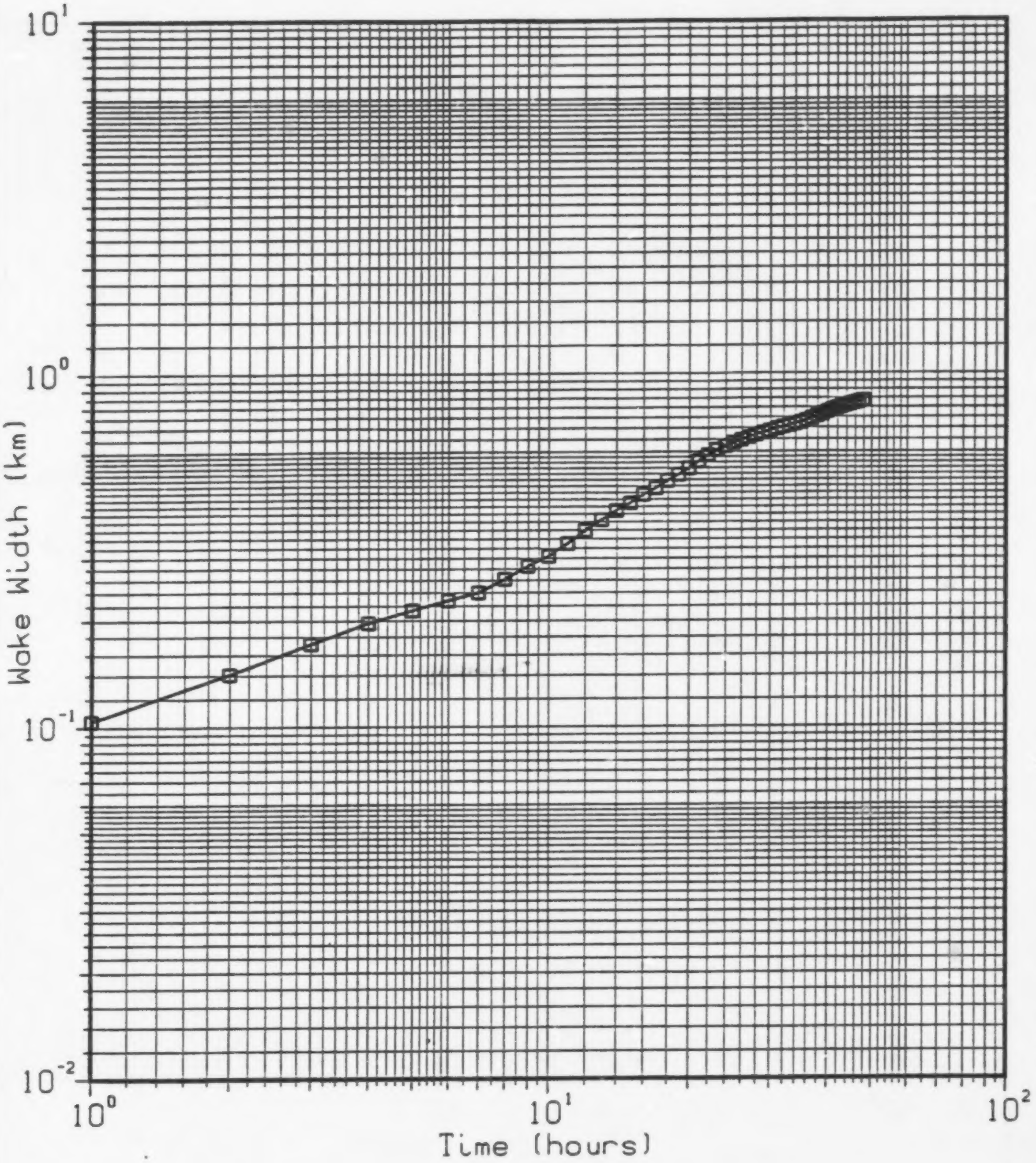


Figure 8. Growth of the pollutant wake downstream from the BOF platform, August 24, 1978

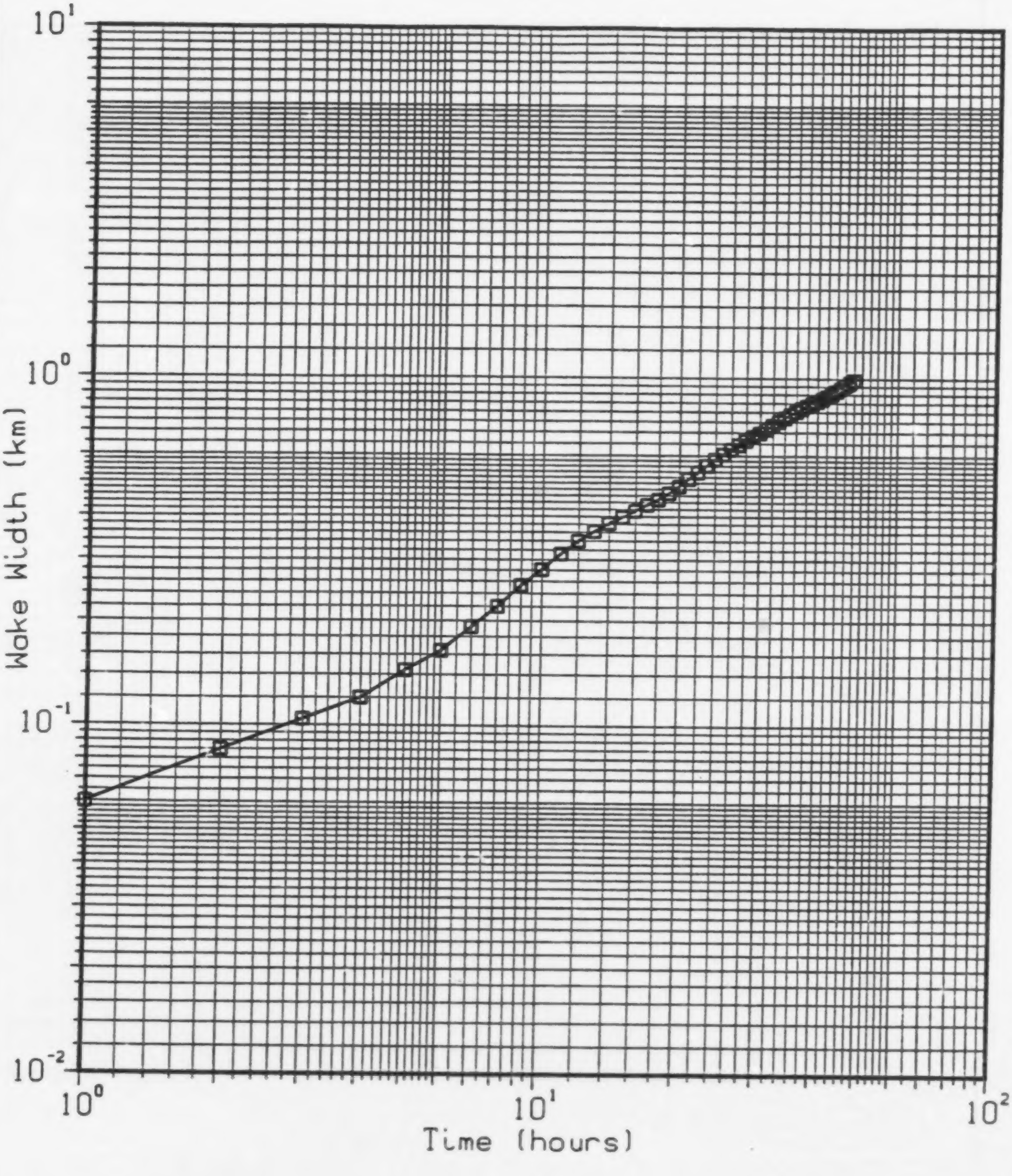


Figure 9. Growth of the pollutant wake downstream from the BOF platform, February 16, 1979

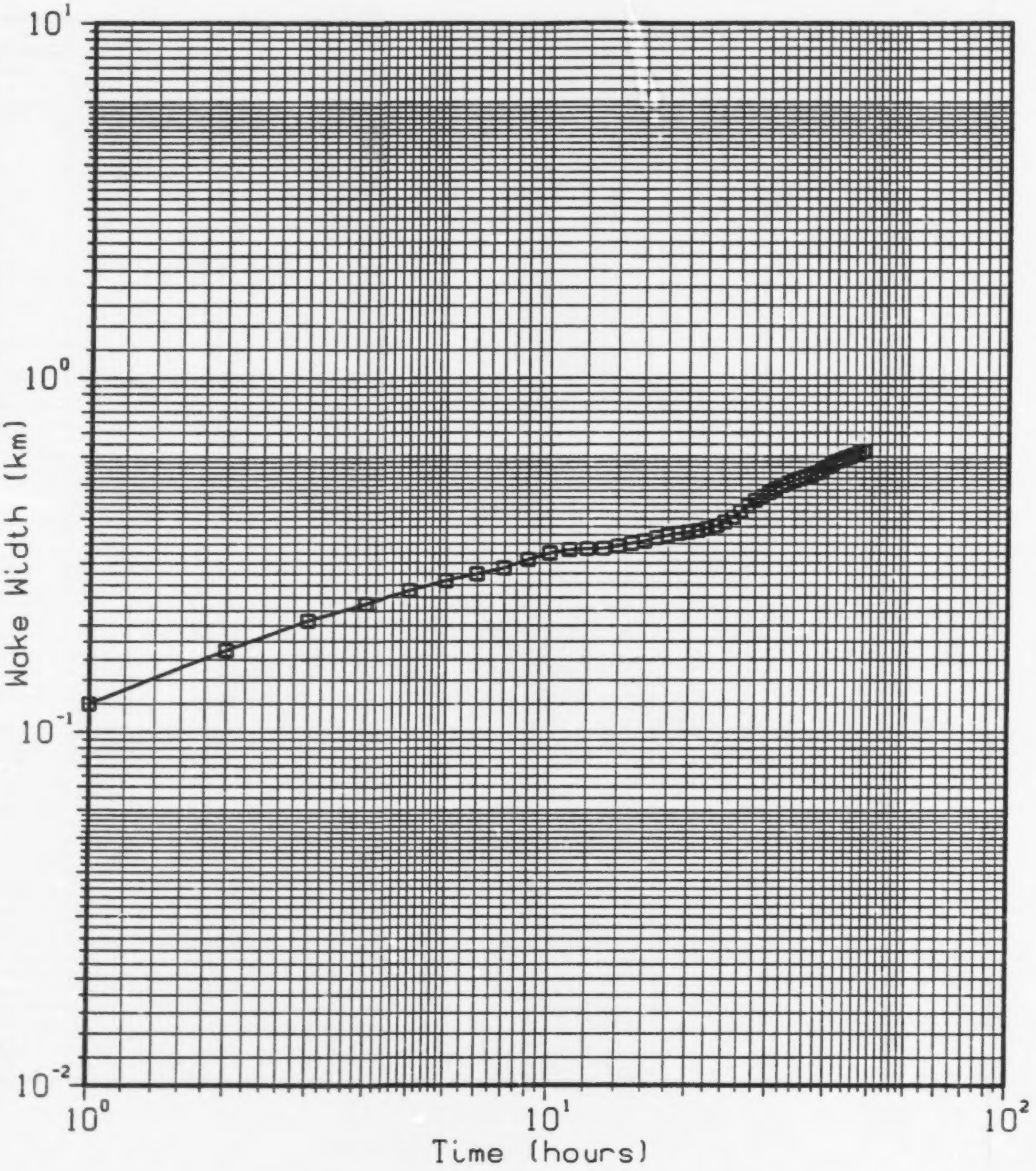


Figure 10. Growth of the pollutant wake downstream from the BOF platform, February 21, 1979

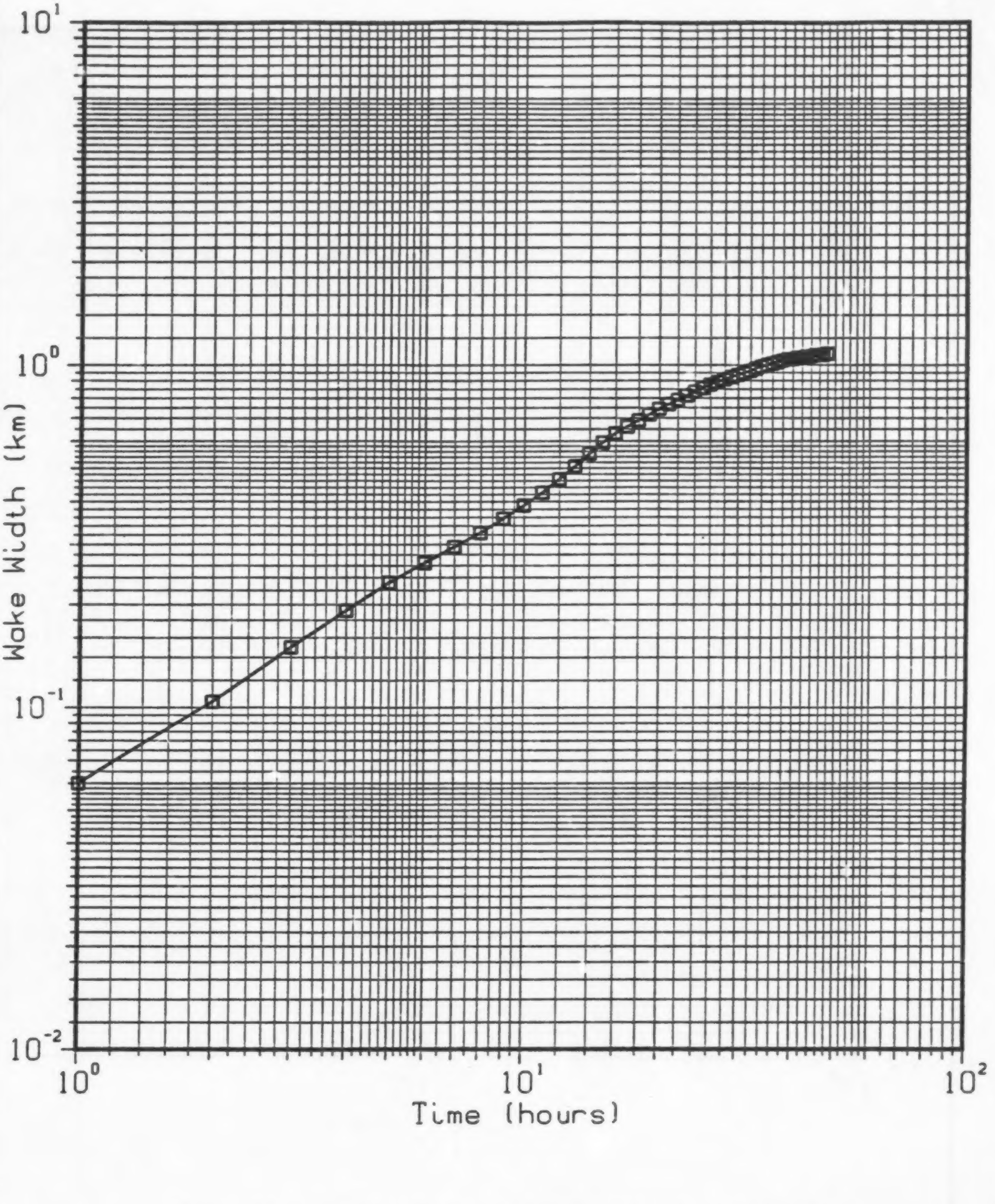


Figure 11. Growth of the pollutant wake downstream from the BOF platform, February 25, 1979

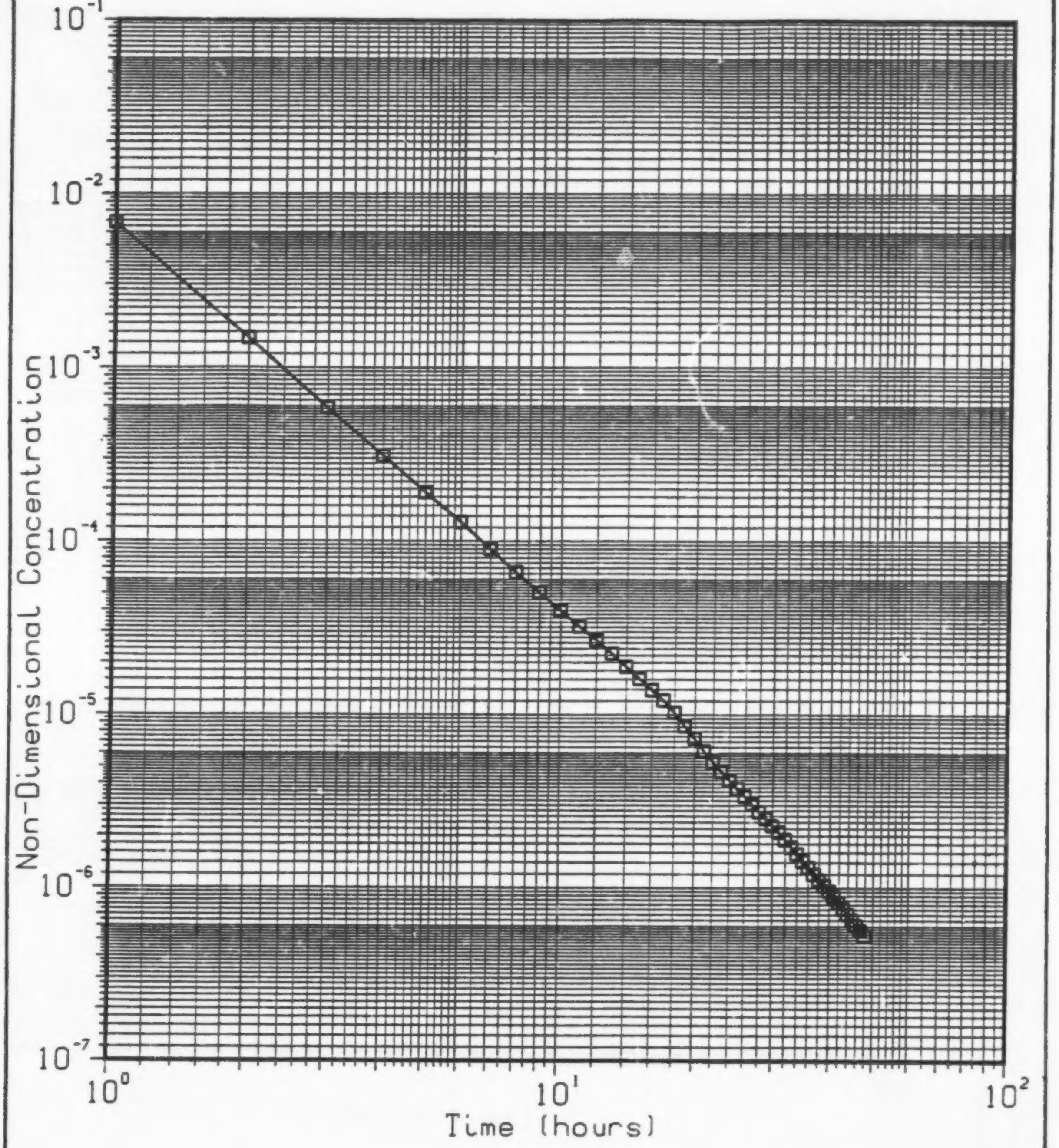


Figure 12. Concentration of vertically distributed pollutants over time, August 4, 1978

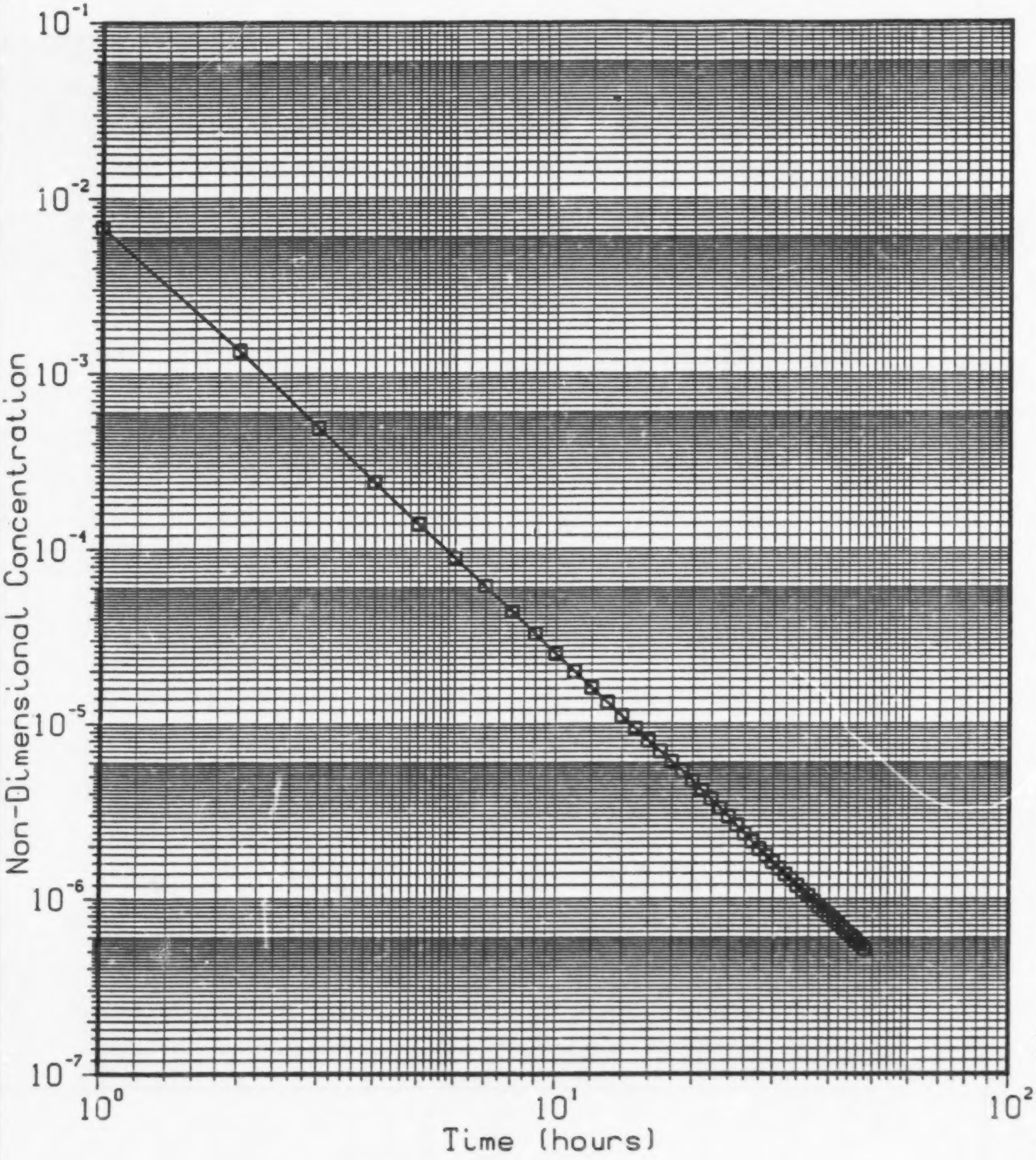


Figure 13. Concentration of vertically distributed pollutants over time, August 8, 1978

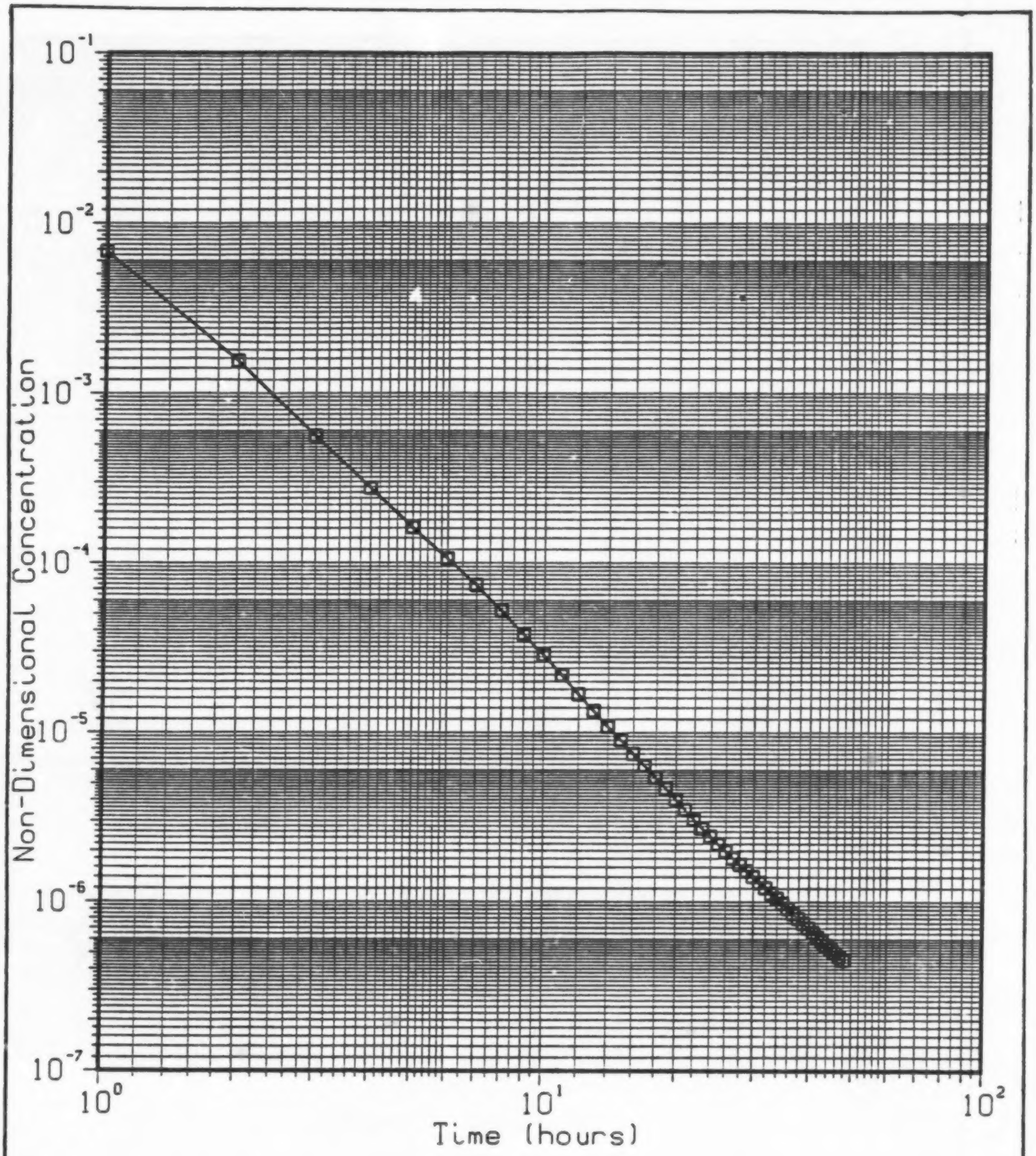


Figure 14. Concentration of vertically distributed pollutants over time, August 24, 1978

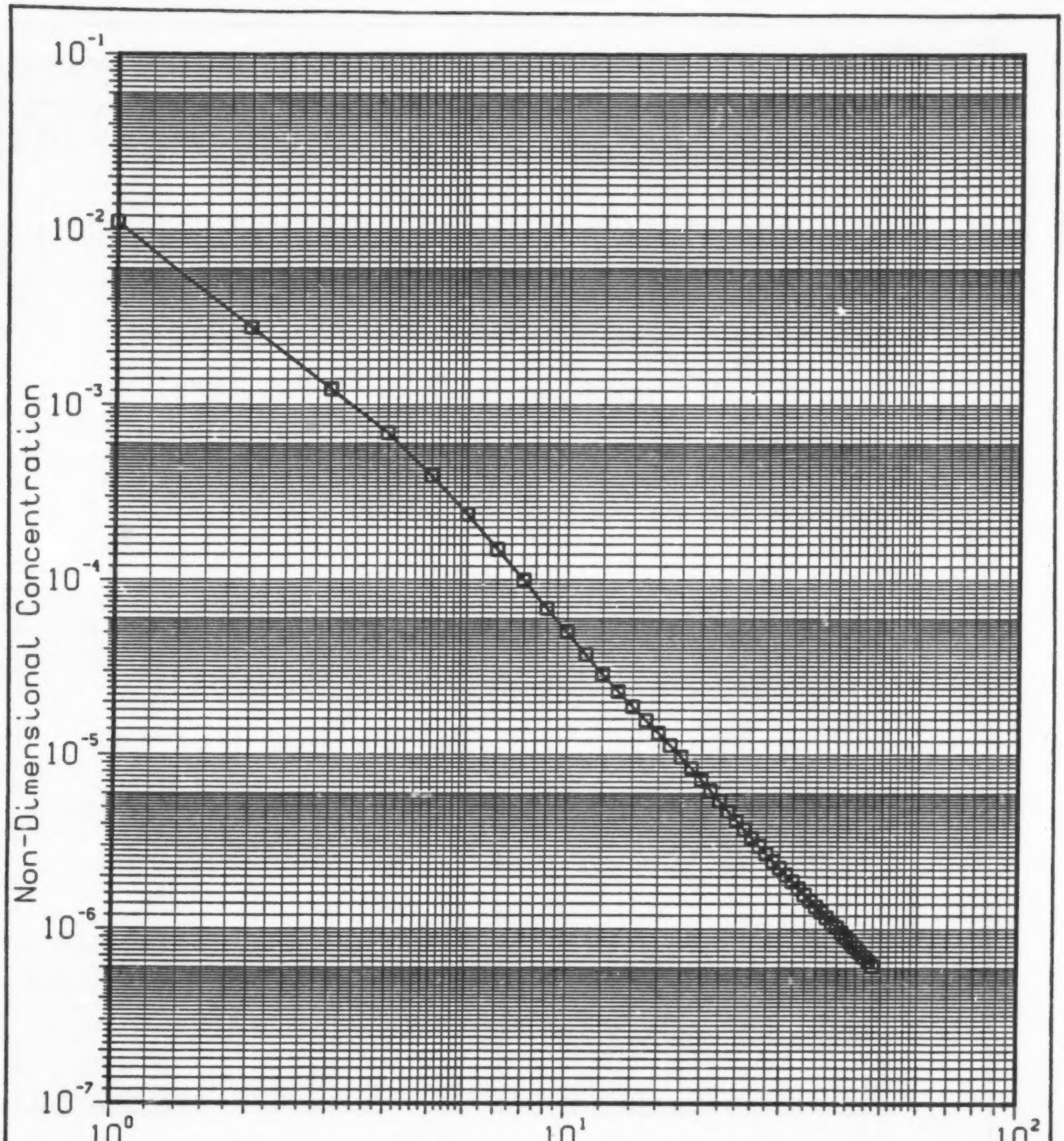


Figure 15. Concentration of vertically distributed pollutants over time, February 16, 1979

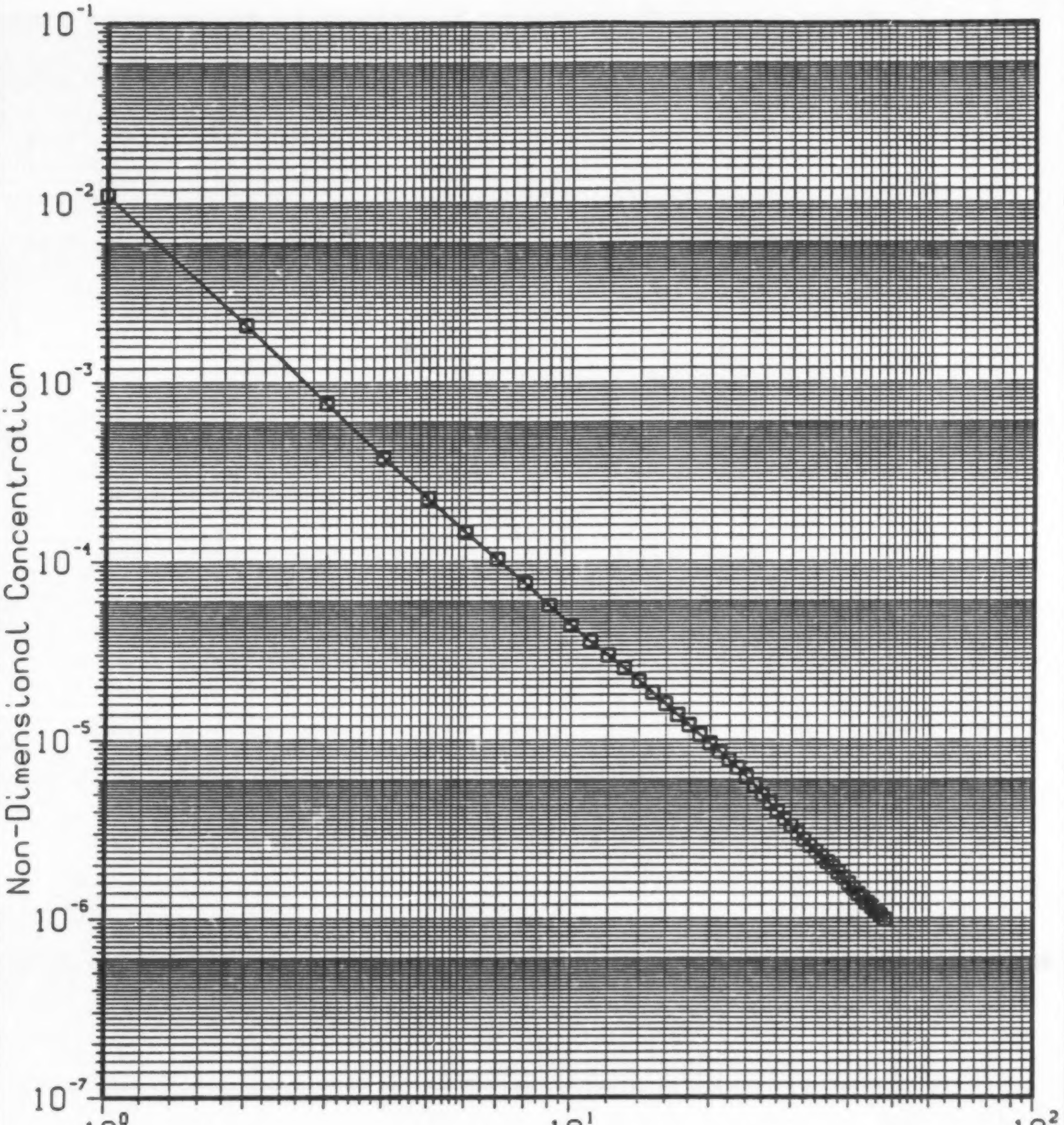


Figure 16. Concentration of vertically distributed pollutants over time, February 21, 1979

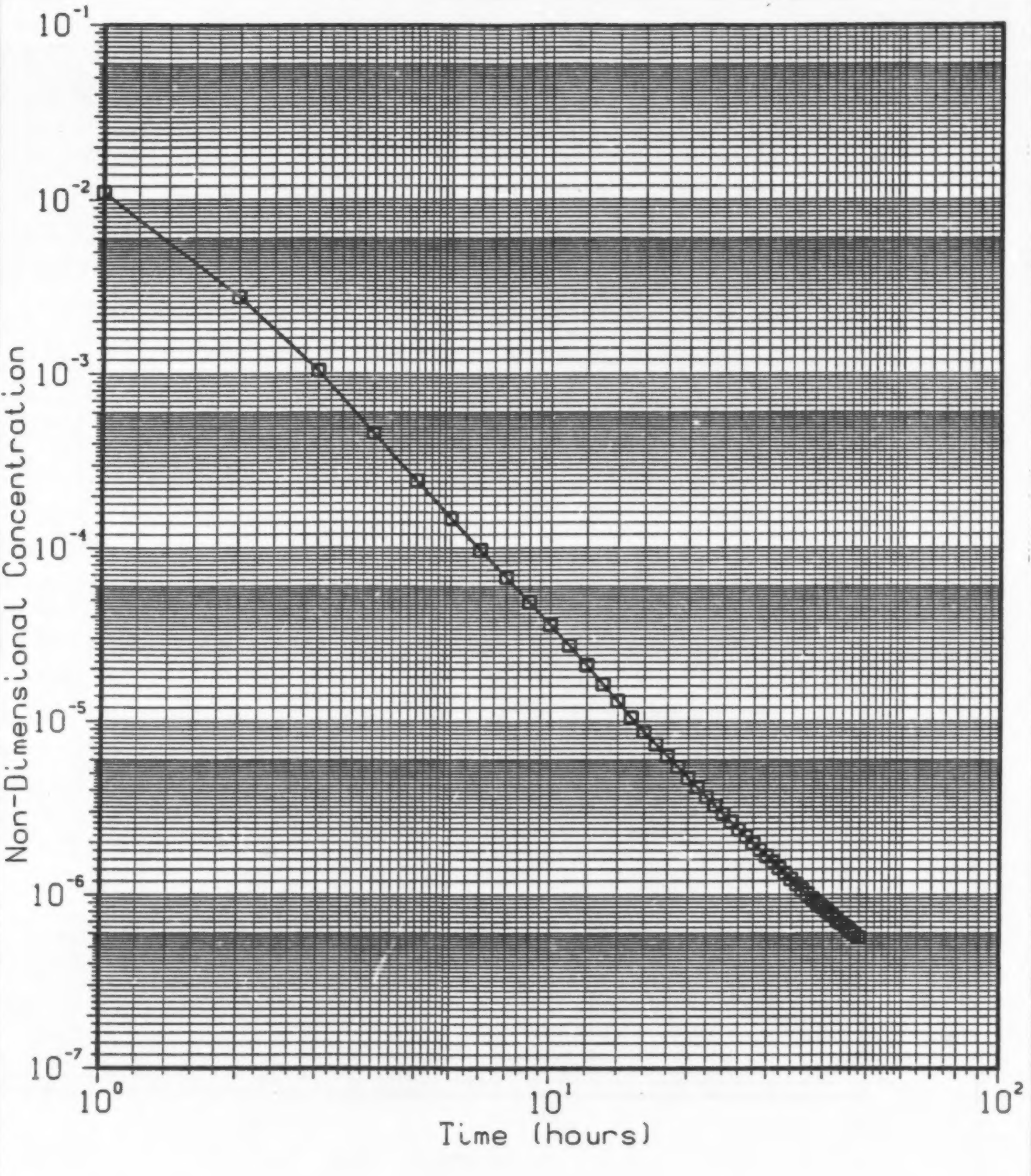


Figure 17. Concentration of vertically distributed pollutants over time, February 25, 1979

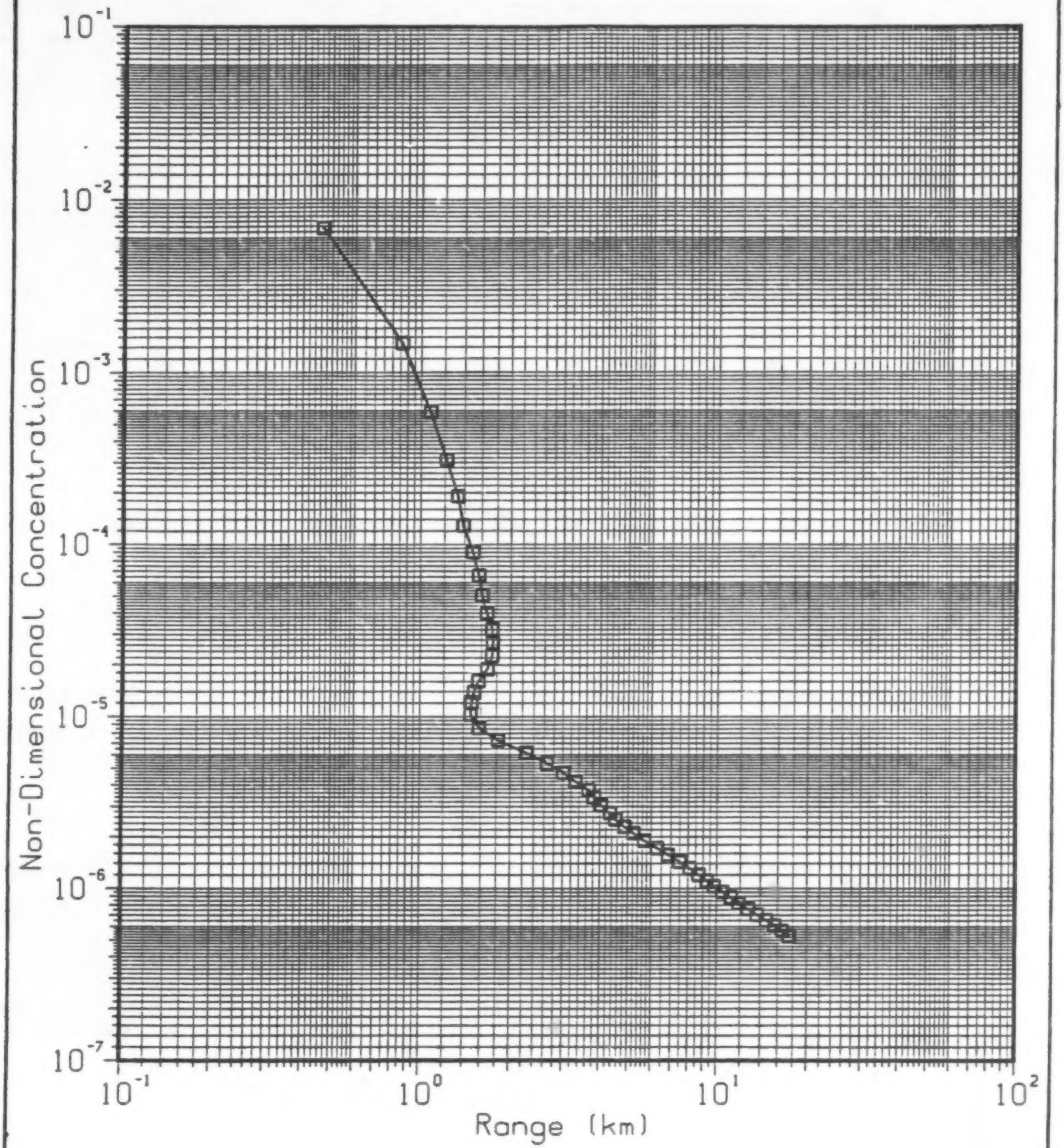


Figure 18. Concentration of vertically distributed pollutants over range, August 4, 1978

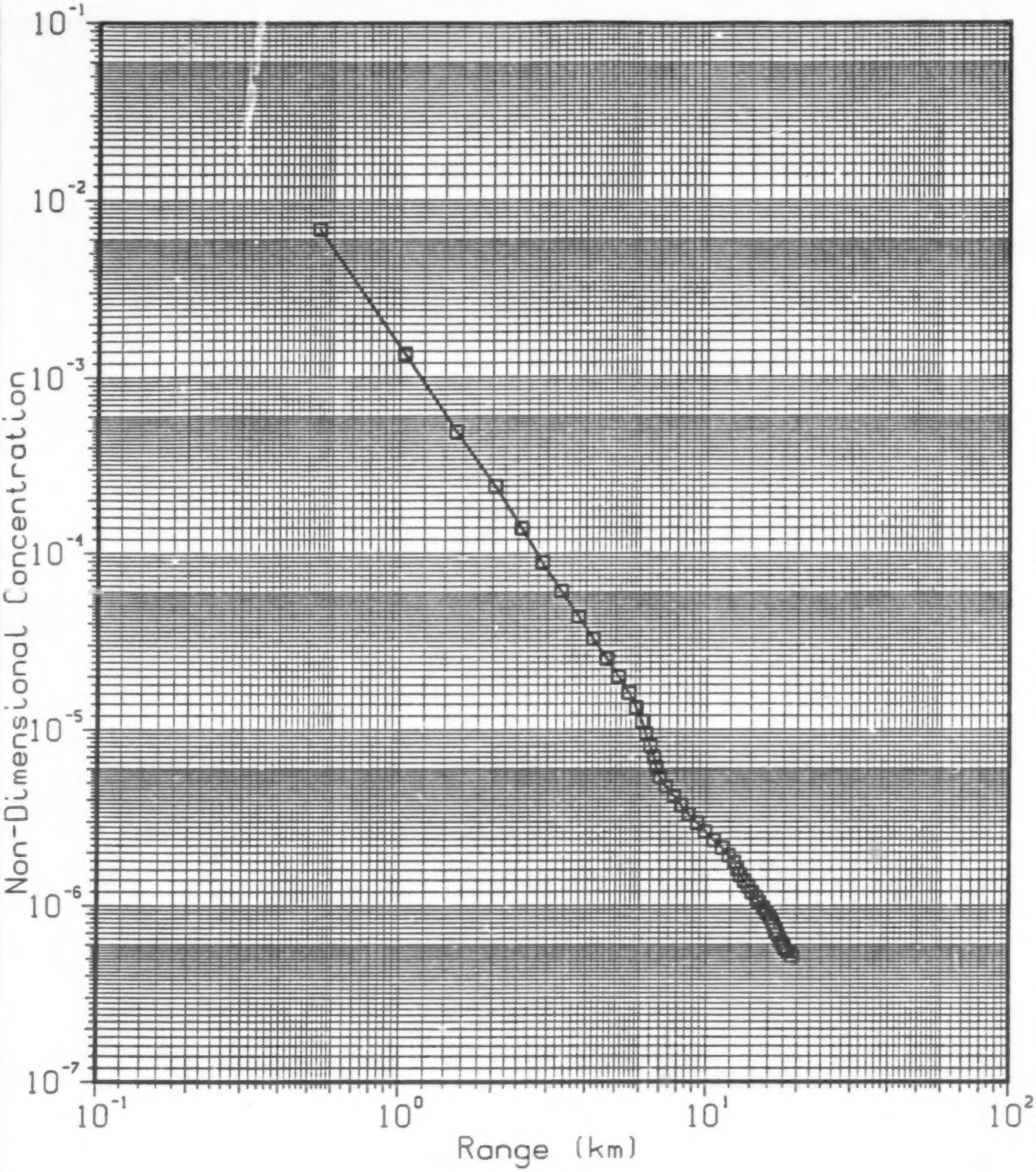


Figure 19. Concentration of vertically distributed pollutants over range, August 8, 1978

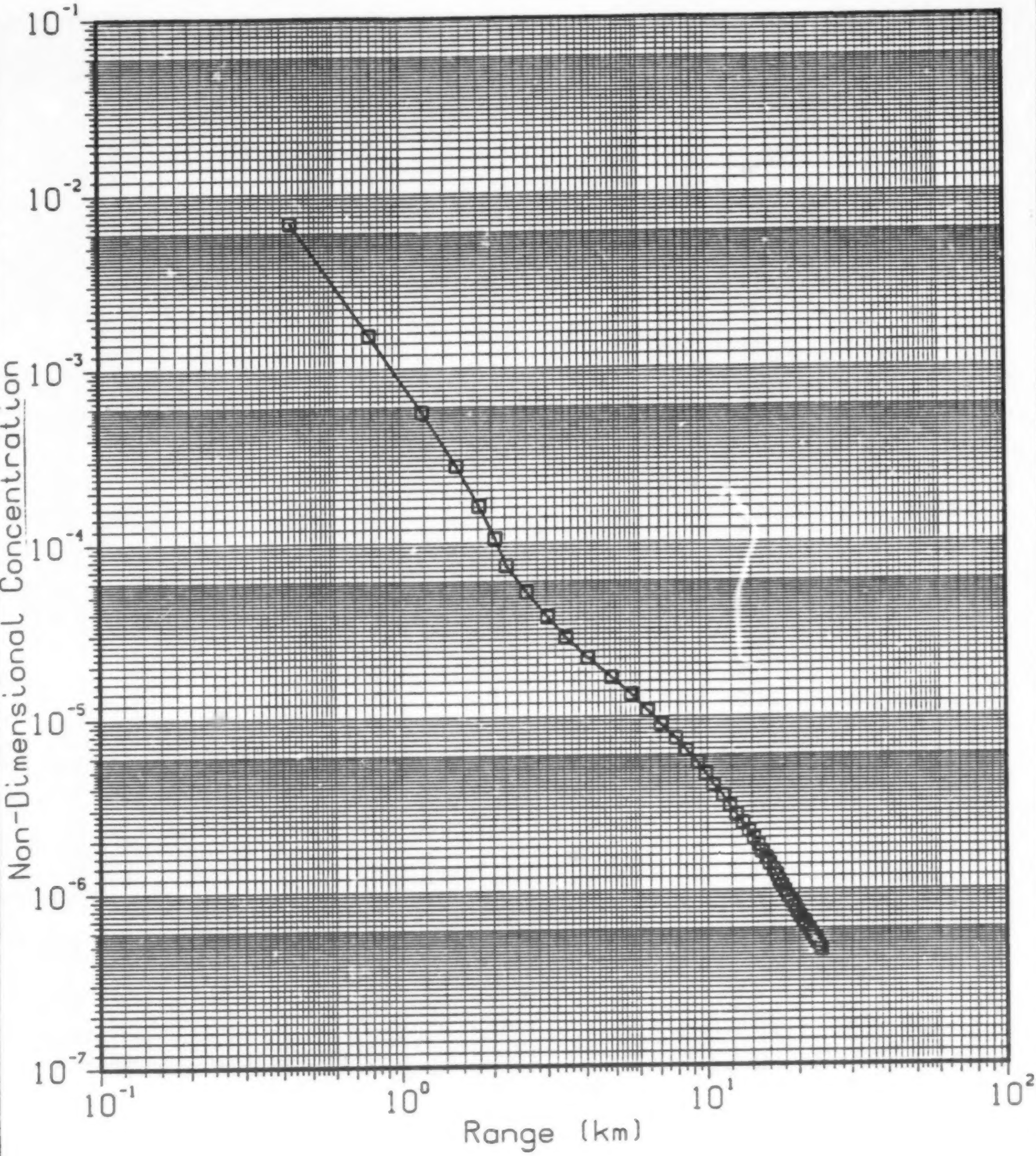


Figure 20. Concentration of vertically distributed pollutants over range, August 24, 1978

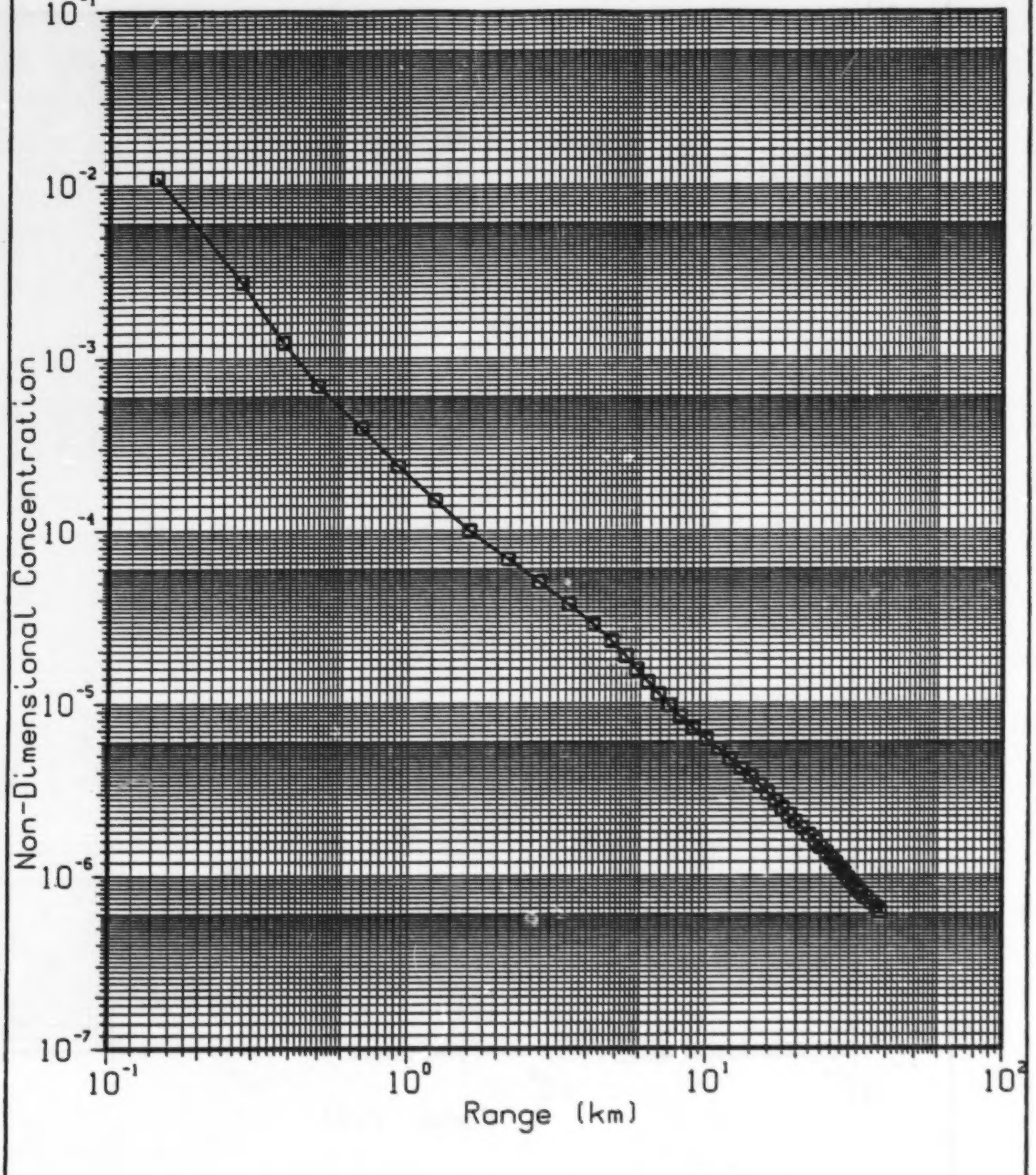


Figure 21. Concentration of vertically distributed pollutants over range, February 16, 1979

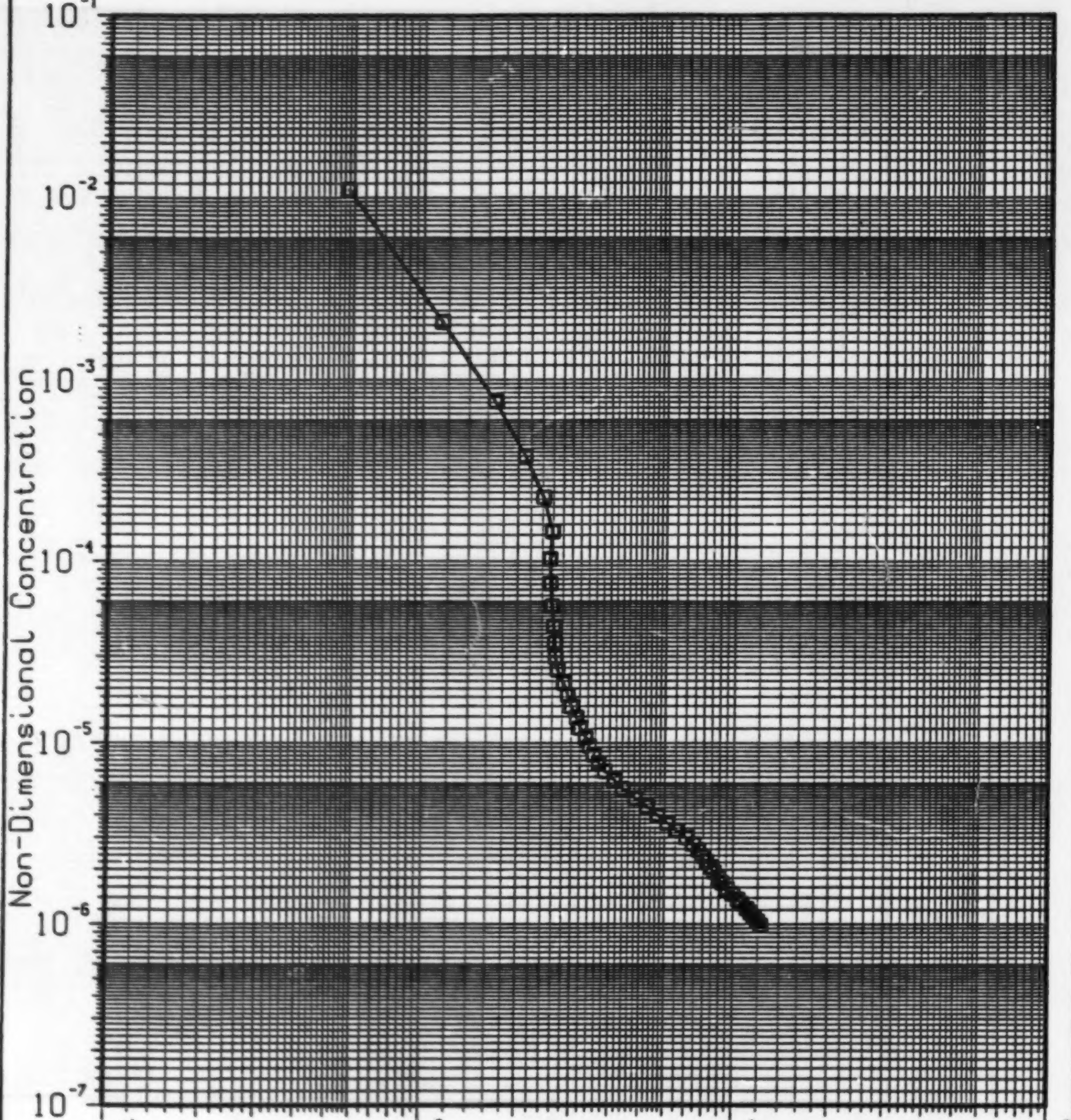


Figure 22. Concentration of vertically distributed pollutants over range, February 21, 1979

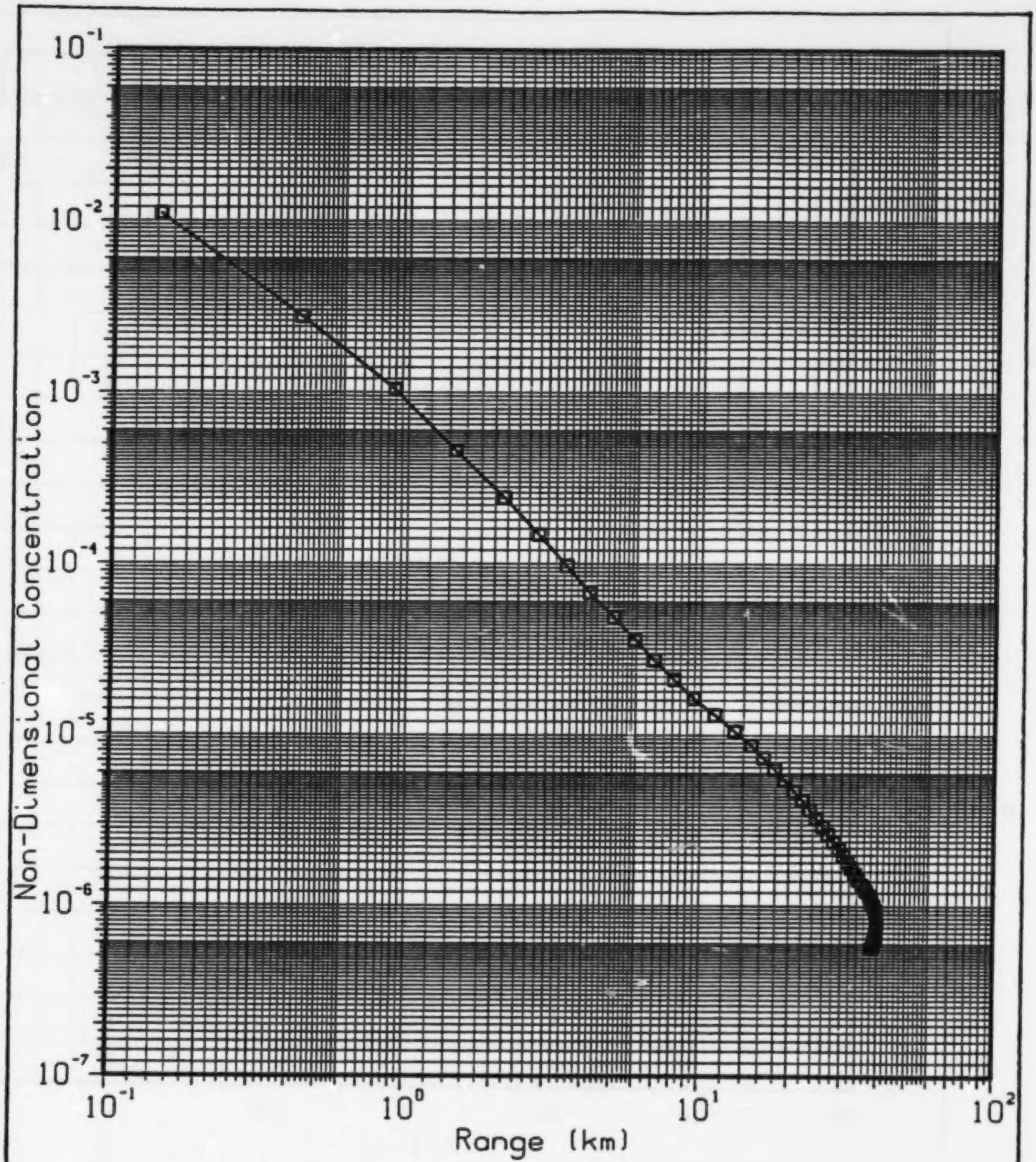


Figure 23. Concentration of vertically distributed pollutants over range, February 25, 1979

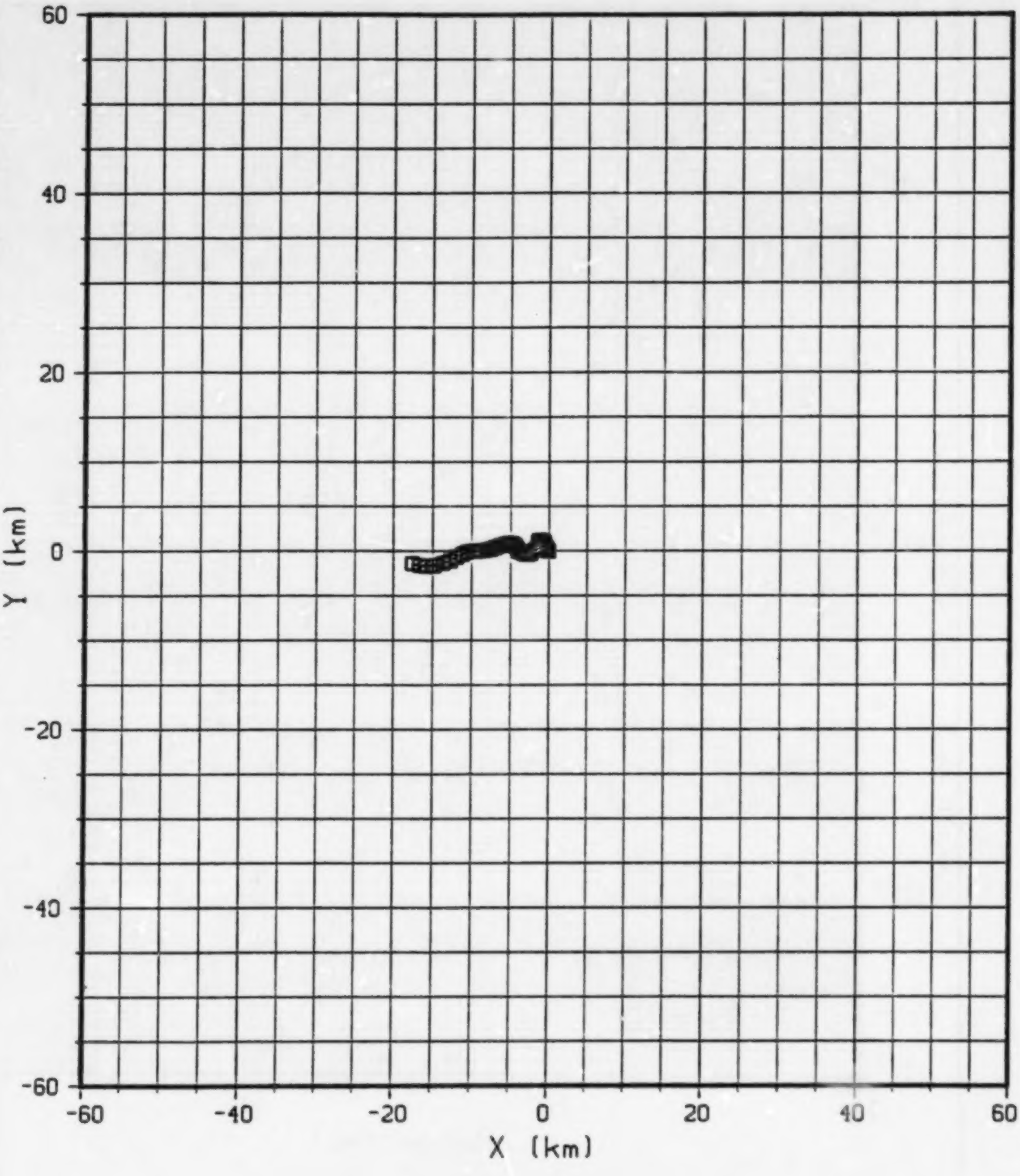


Figure 24. Subsurface pollutant trajectory, August 4, 1978

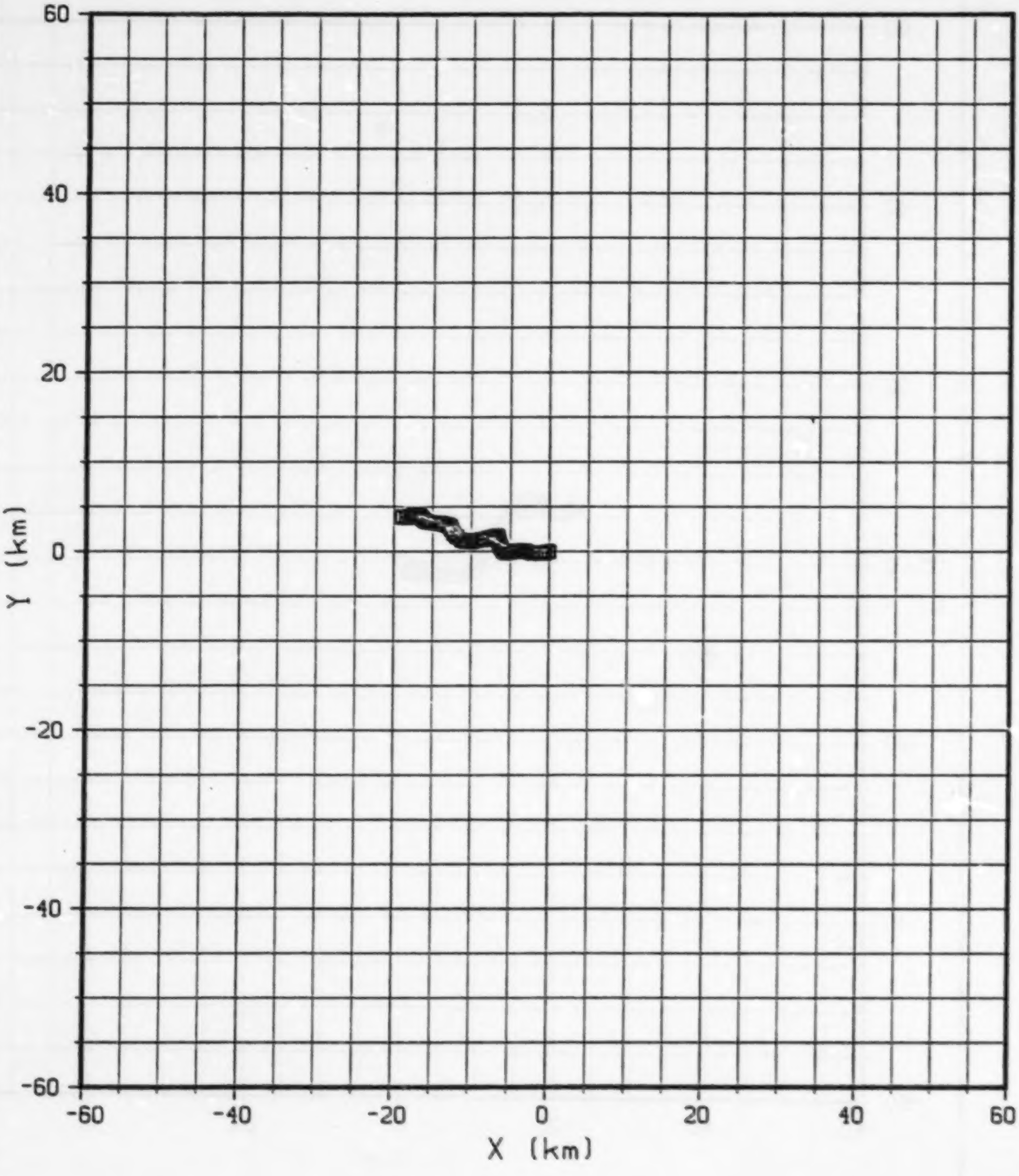


Figure 25. Subsurface pollutant trajectory, August 8, 1978

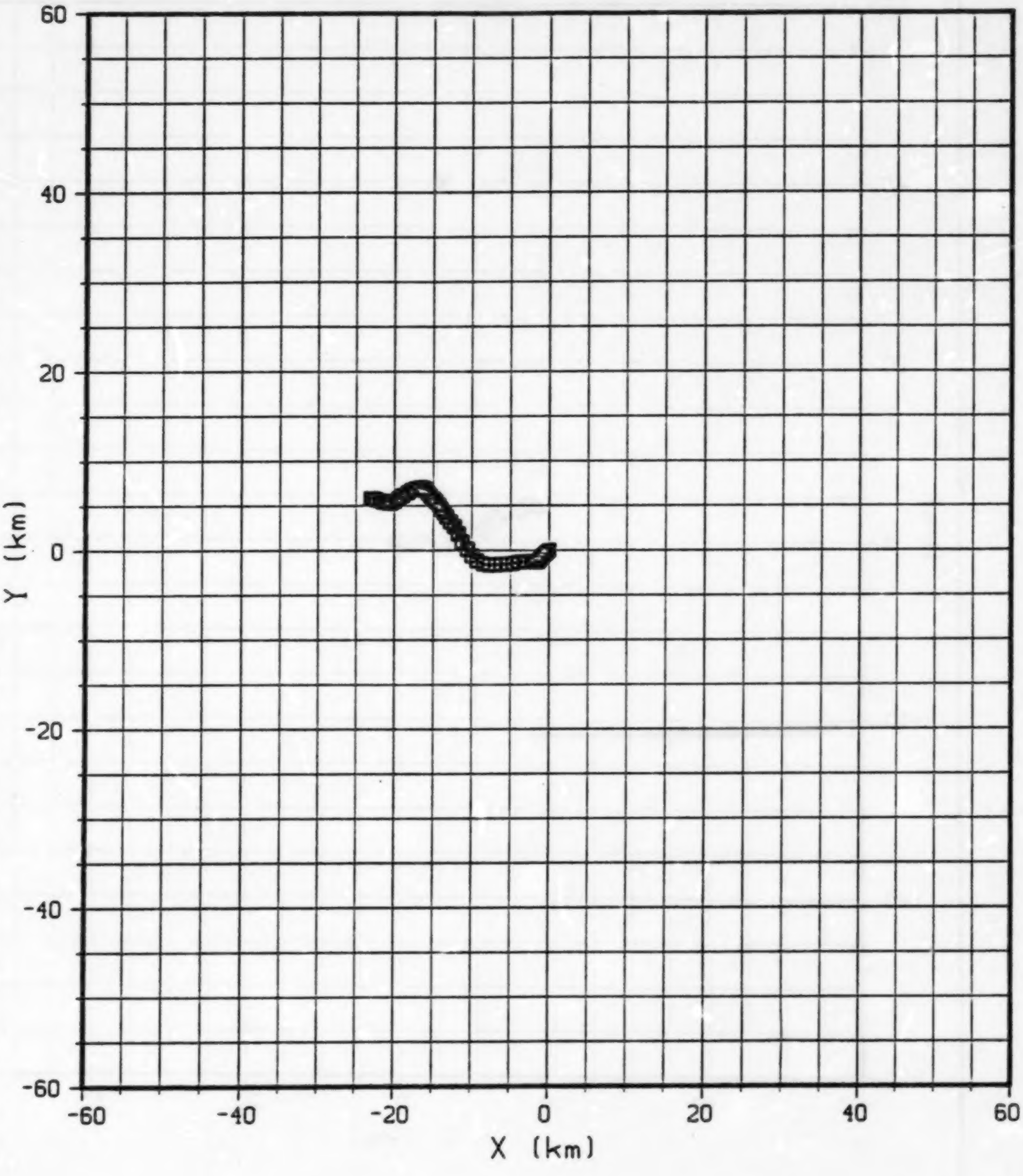


Figure 26. Subsurface pollutant trajectory, August 24, 1978

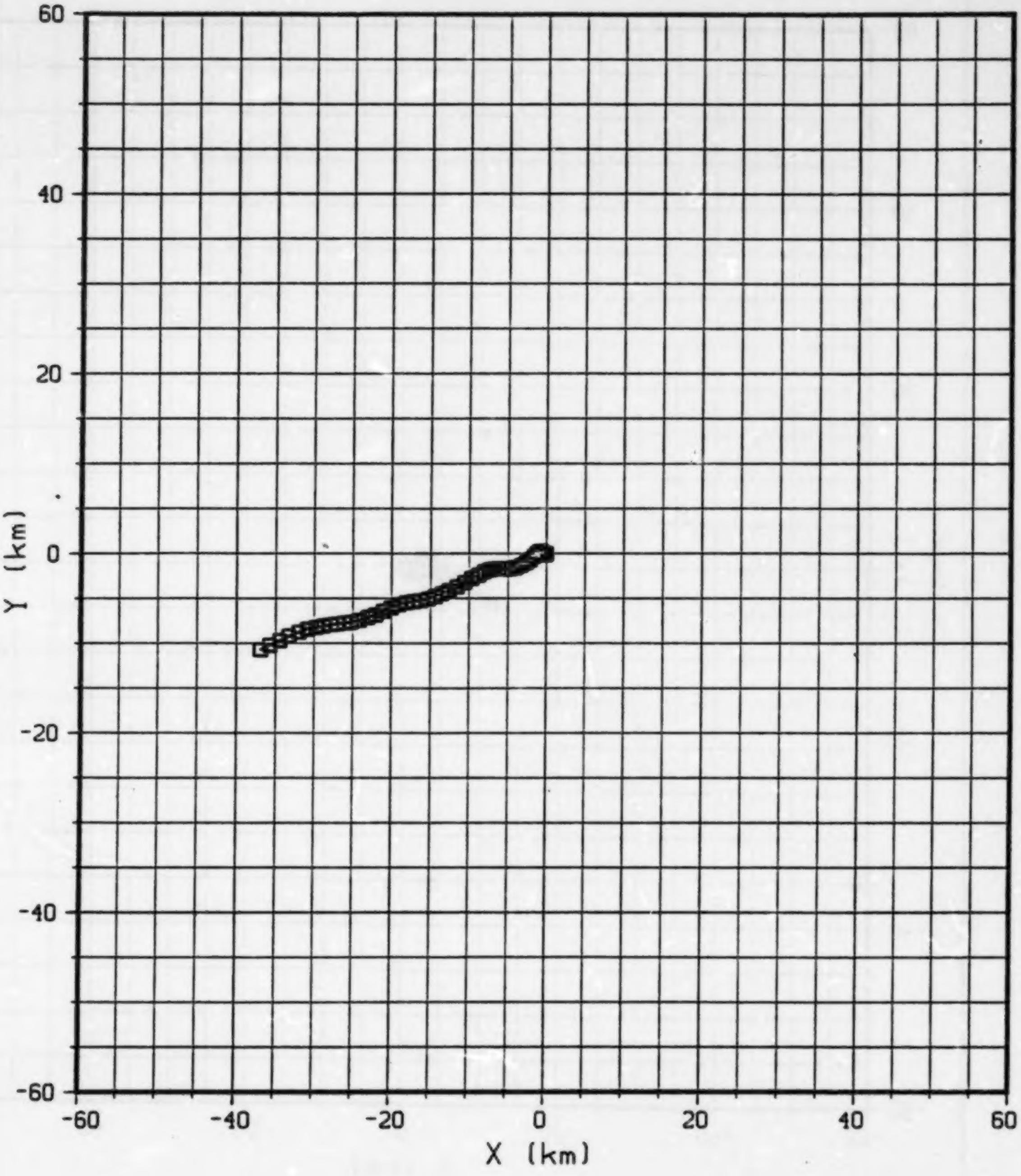


Figure 27. Subsurface pollutant trajectory, February 16, 1979

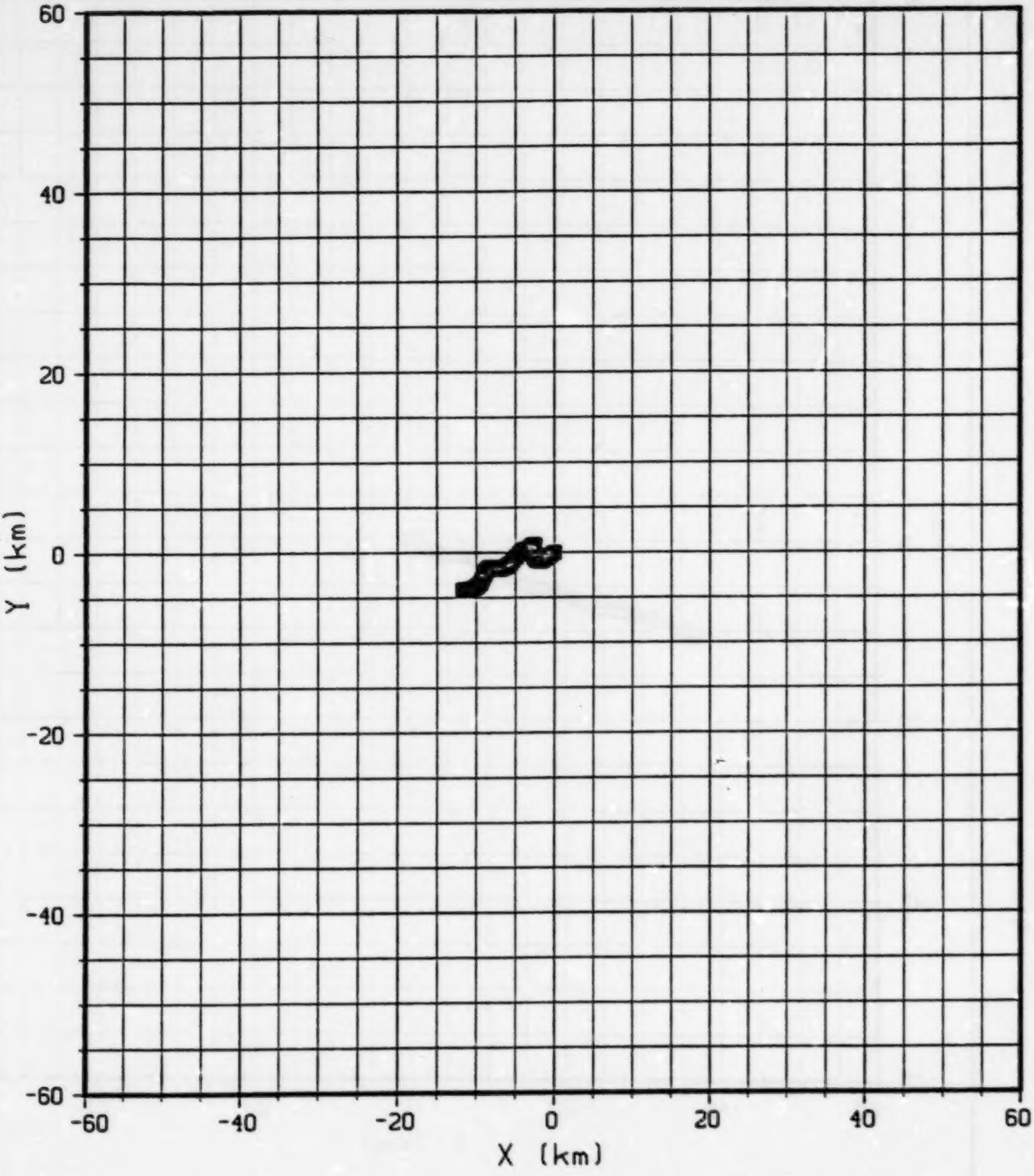


Figure 28. Subsurface pollutant trajectory, February 21, 1979

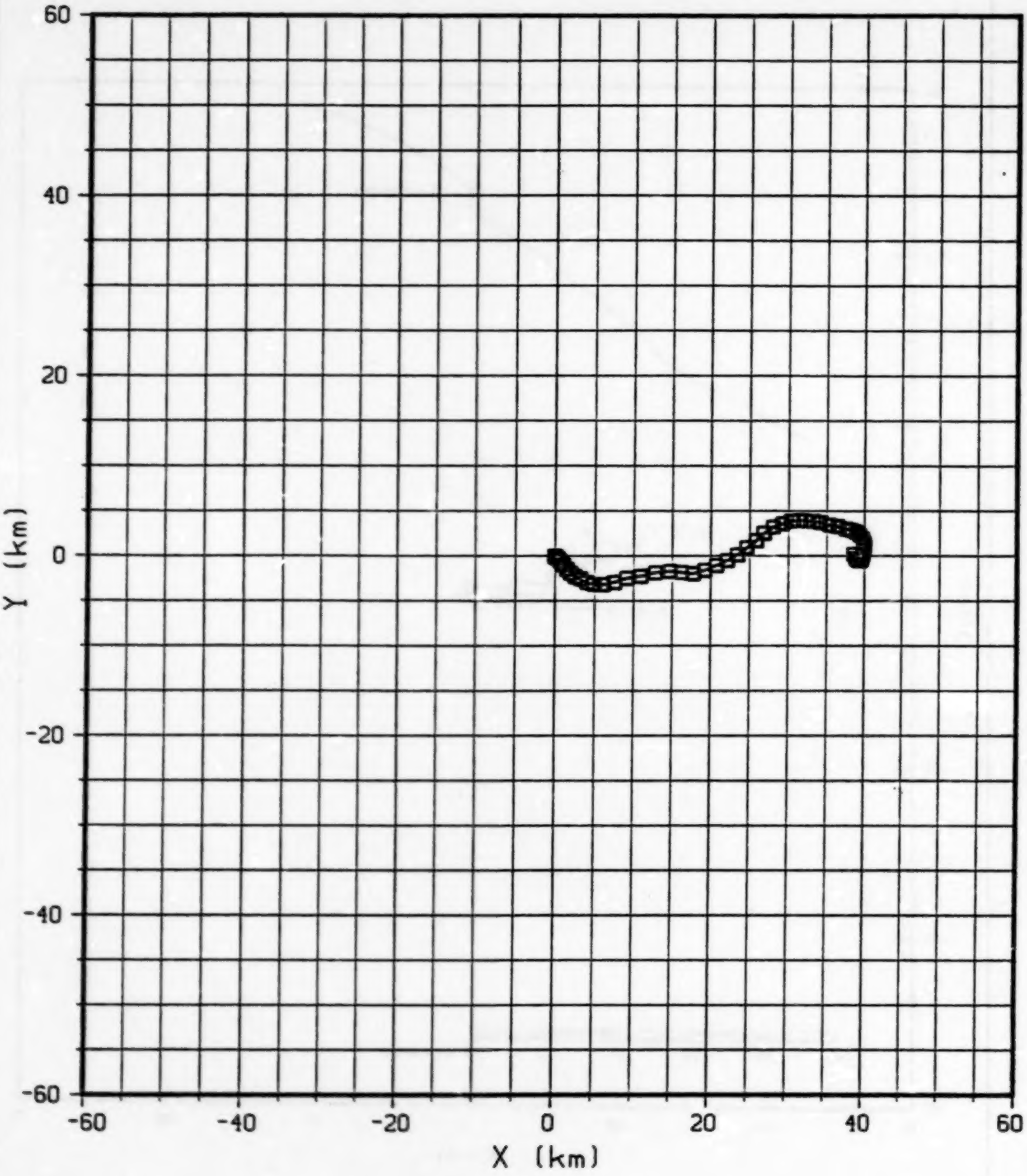


Figure 29. Subsurface pollutant trajectory, February 25, 1979

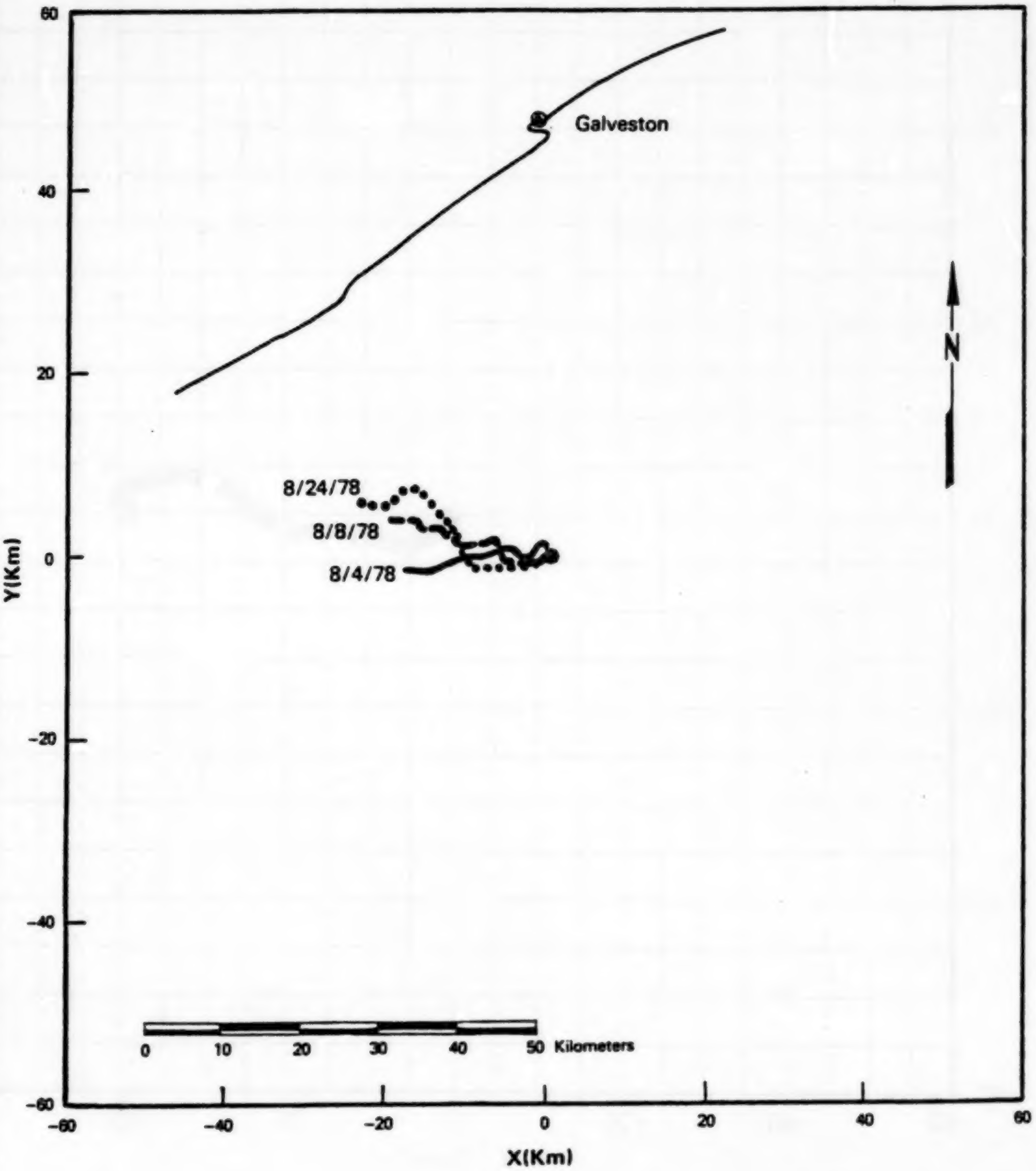
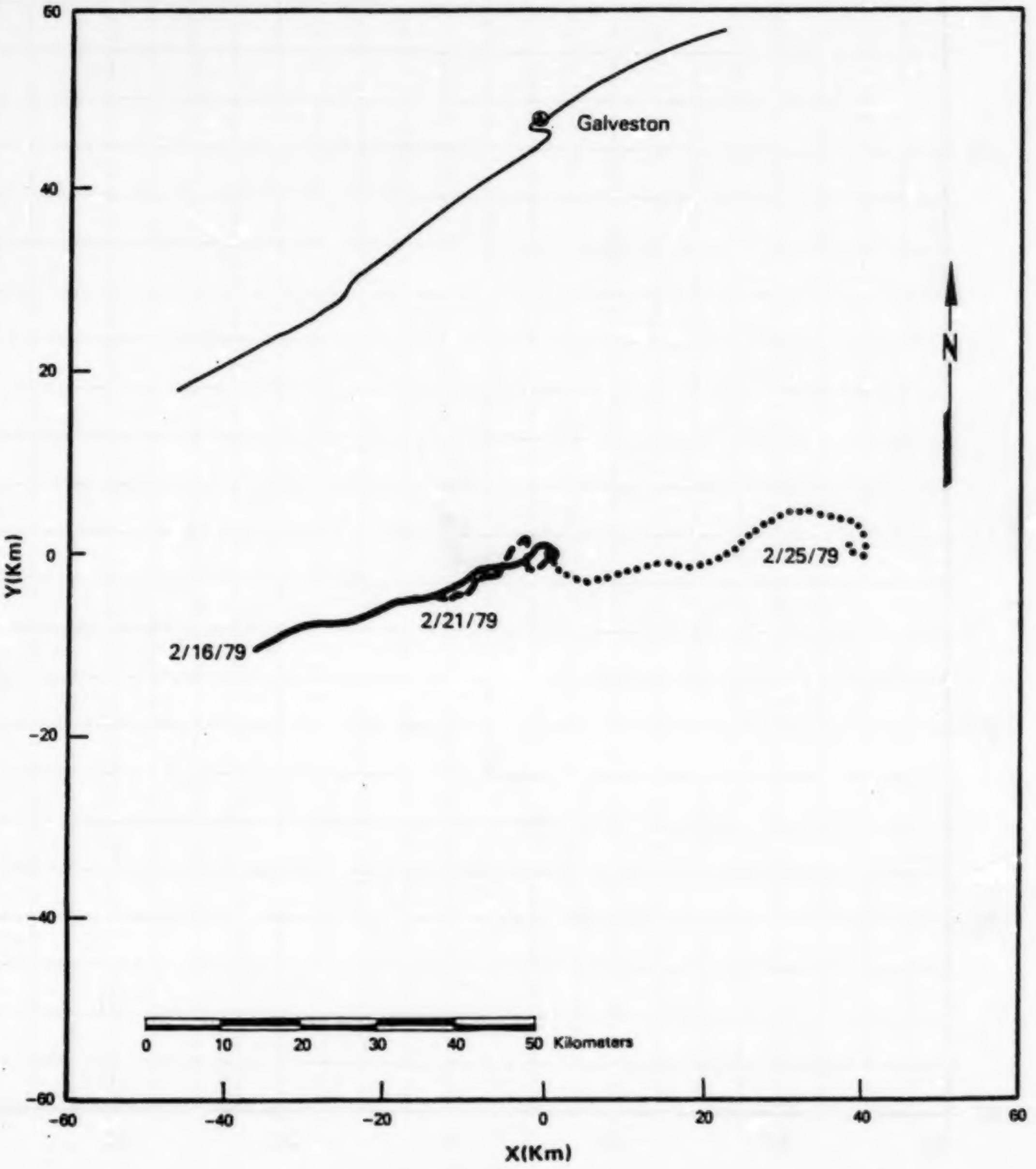

Galveston
N
8/24/78
8/8/78
8/4/78
0 10 20 30 40 50 Kilometers
60
40
20
0
-20
-40
-60
Y(Km)
-60 -40 -20 0 20 40 60
X(Km)

Figure 30. Composite map of subsurface pollutant trajectories, August 1978



60
40
20
0
-20
-40
-60
Y(Km)
-60
-40
-20
0
20
40
60
X(Km)
Galveston
N
2/16/79
2/21/79
2/25/79
0
10
20
30
40
50
Kilometers

Figure 31. Composite map of subsurface pollutant trajectories, February 1979

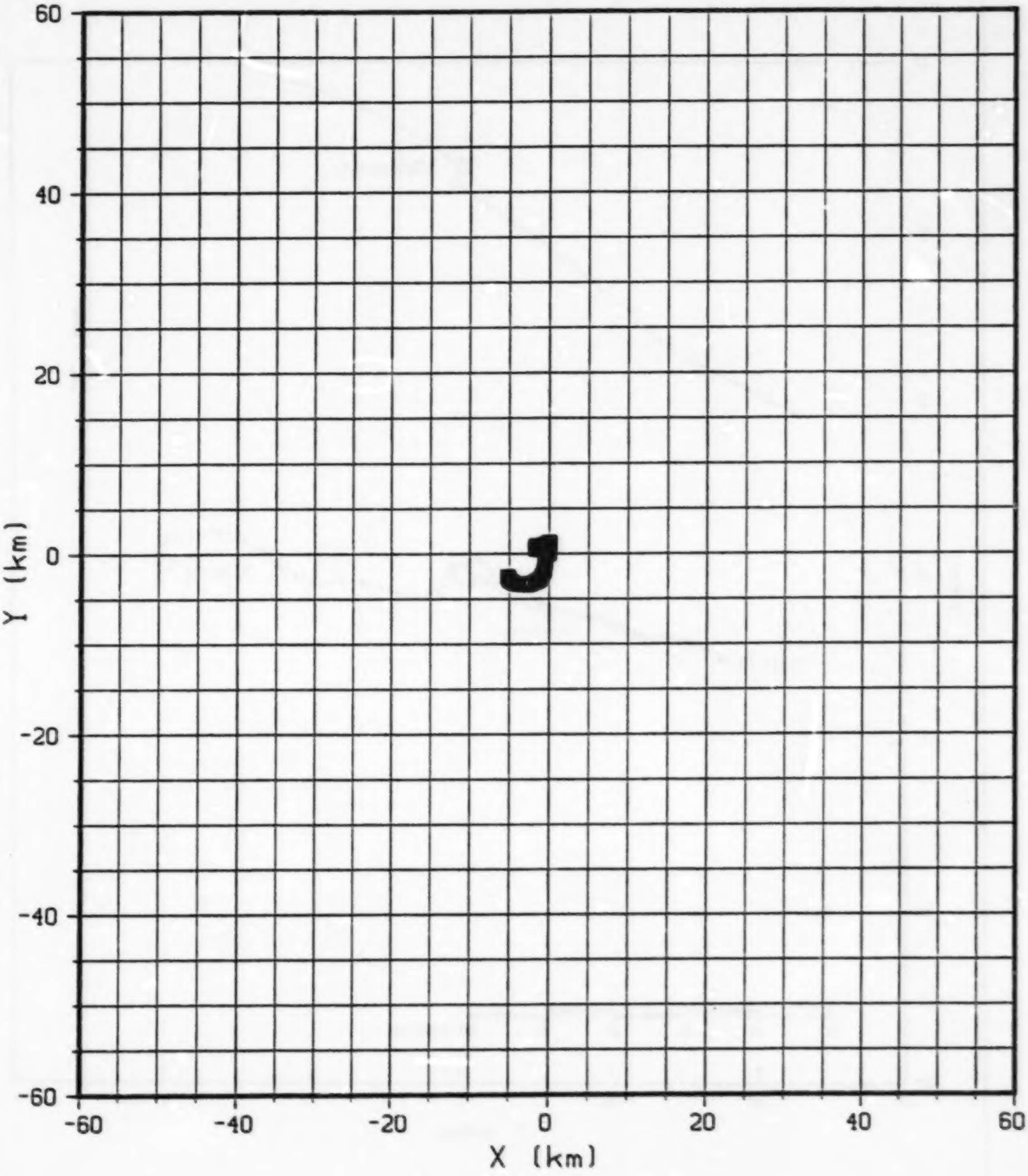


Figure 32. Floating pollutant trajectory, August 4, 1978

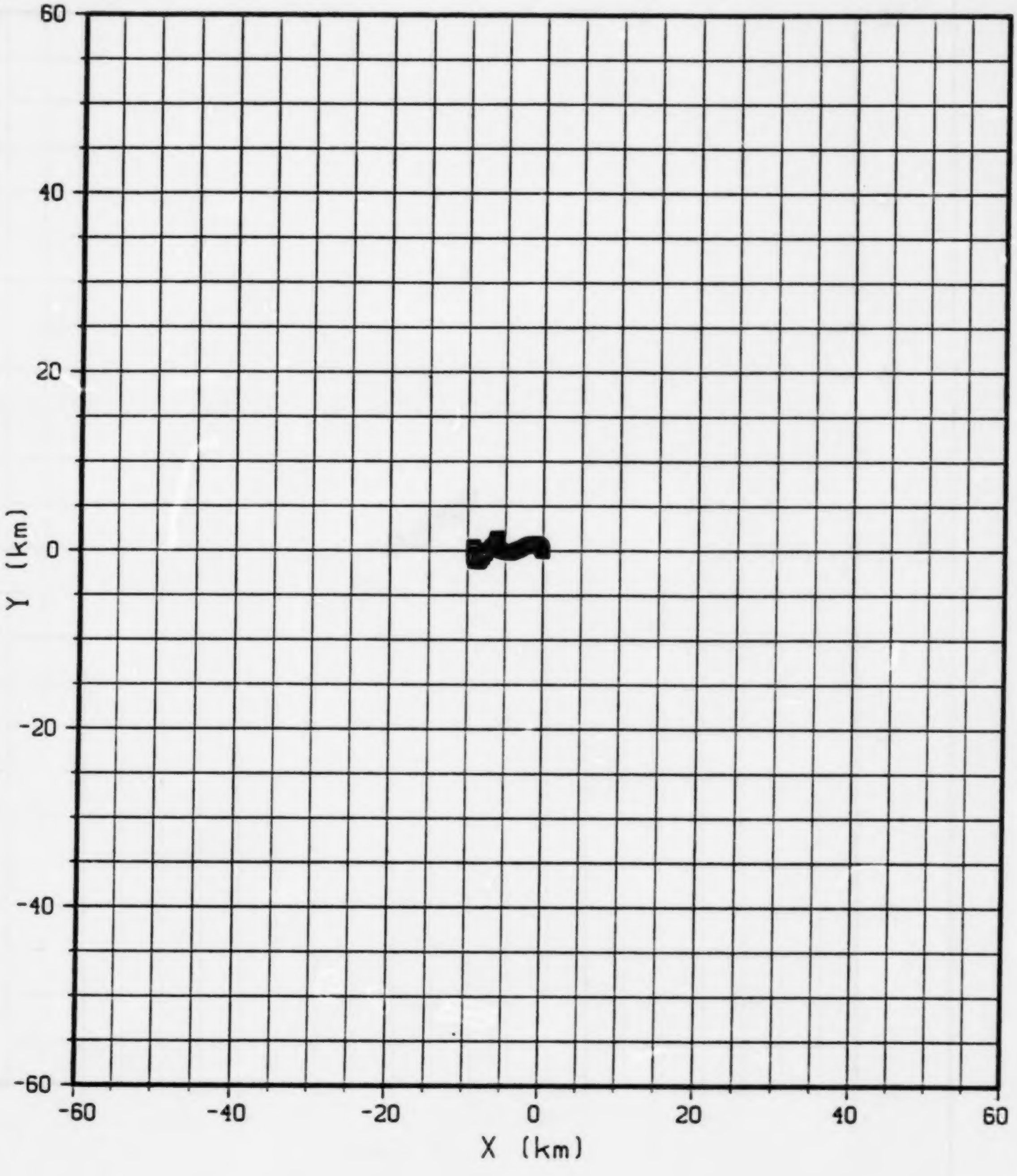


Figure 33. Floating pollutant trajectory,
August 8, 1978

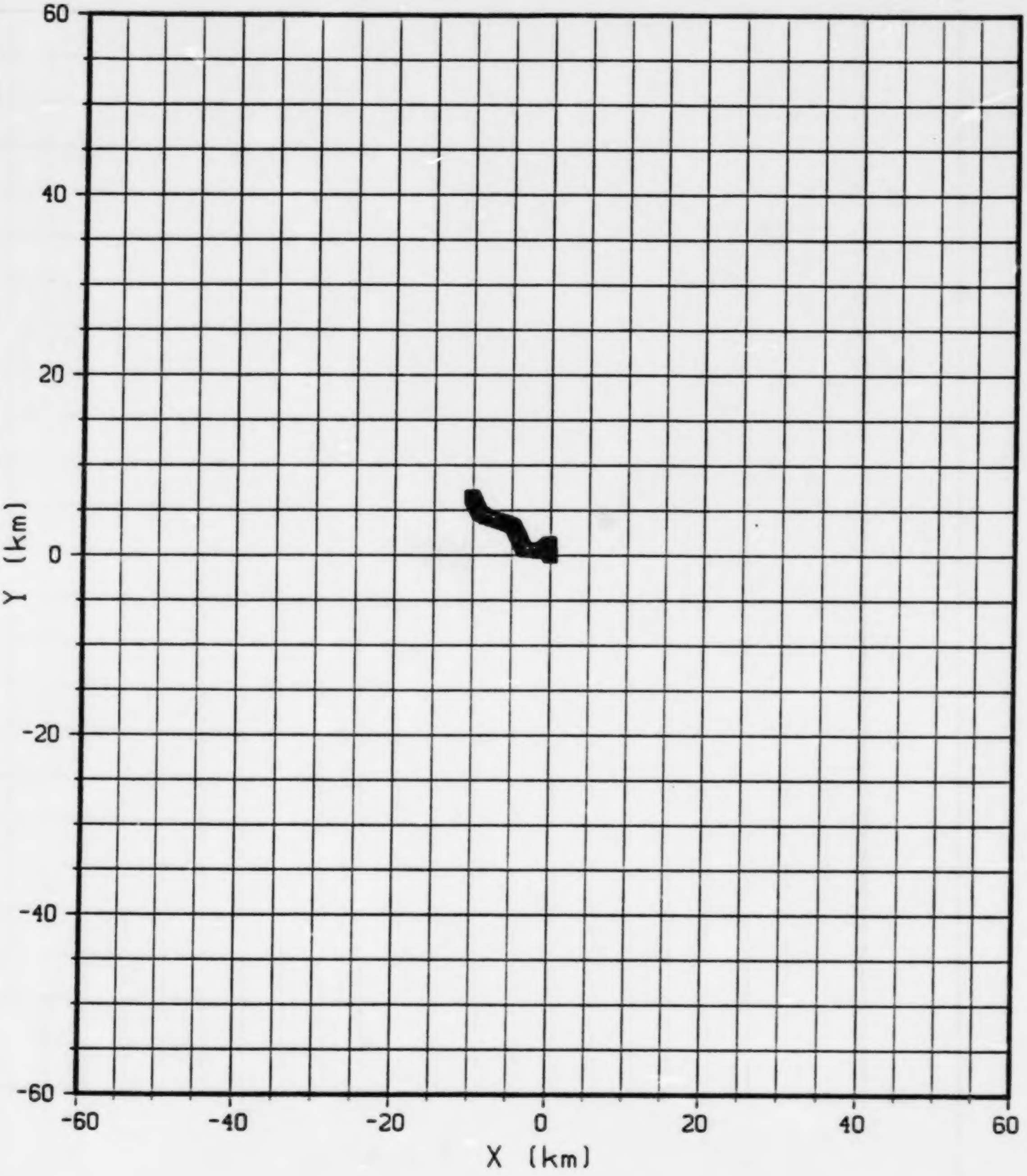


Figure 34. Floating pollutant trajectory, August 24, 1978

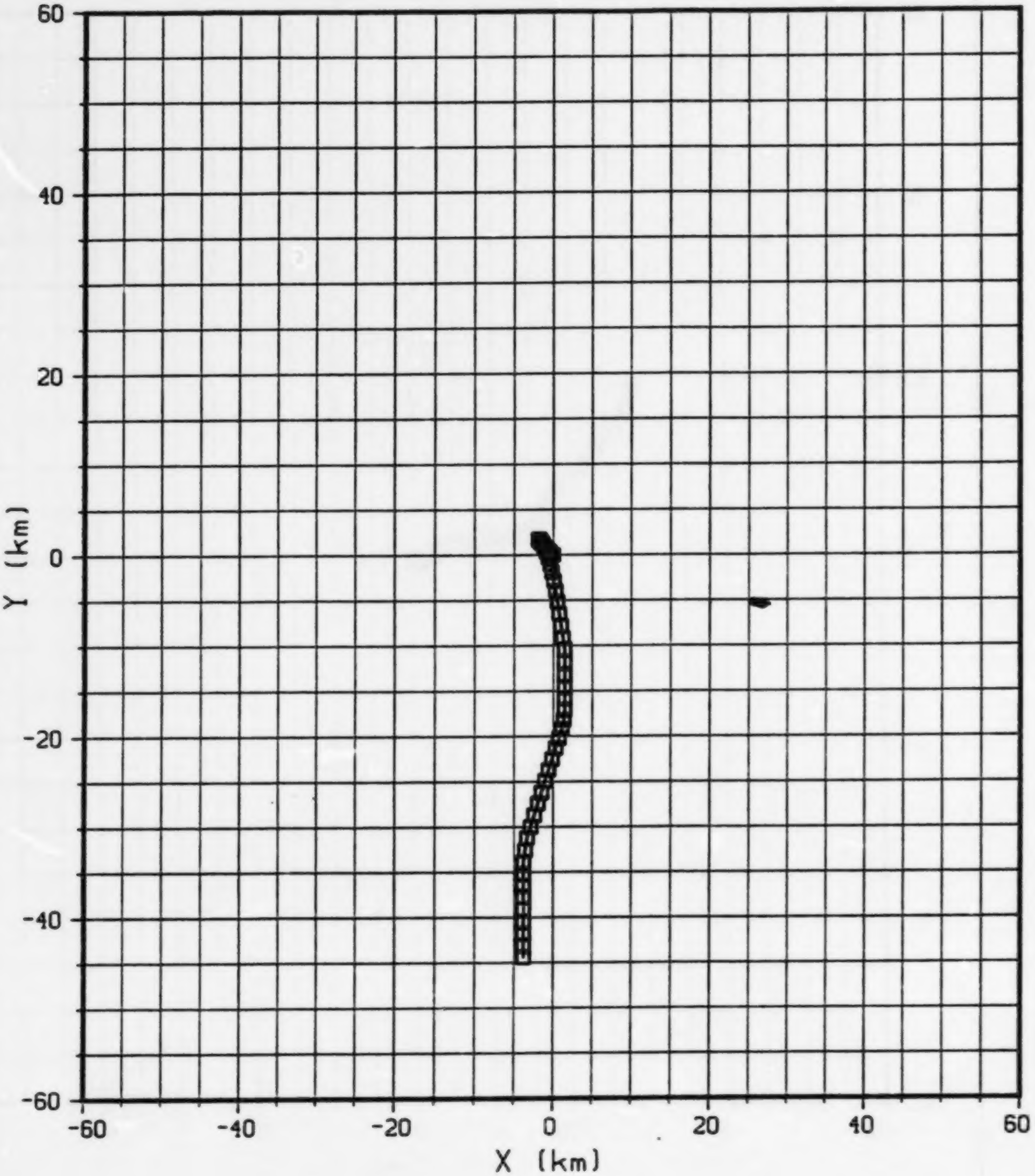


Figure 35. Floating pollutant trajectory, February 16, 1979

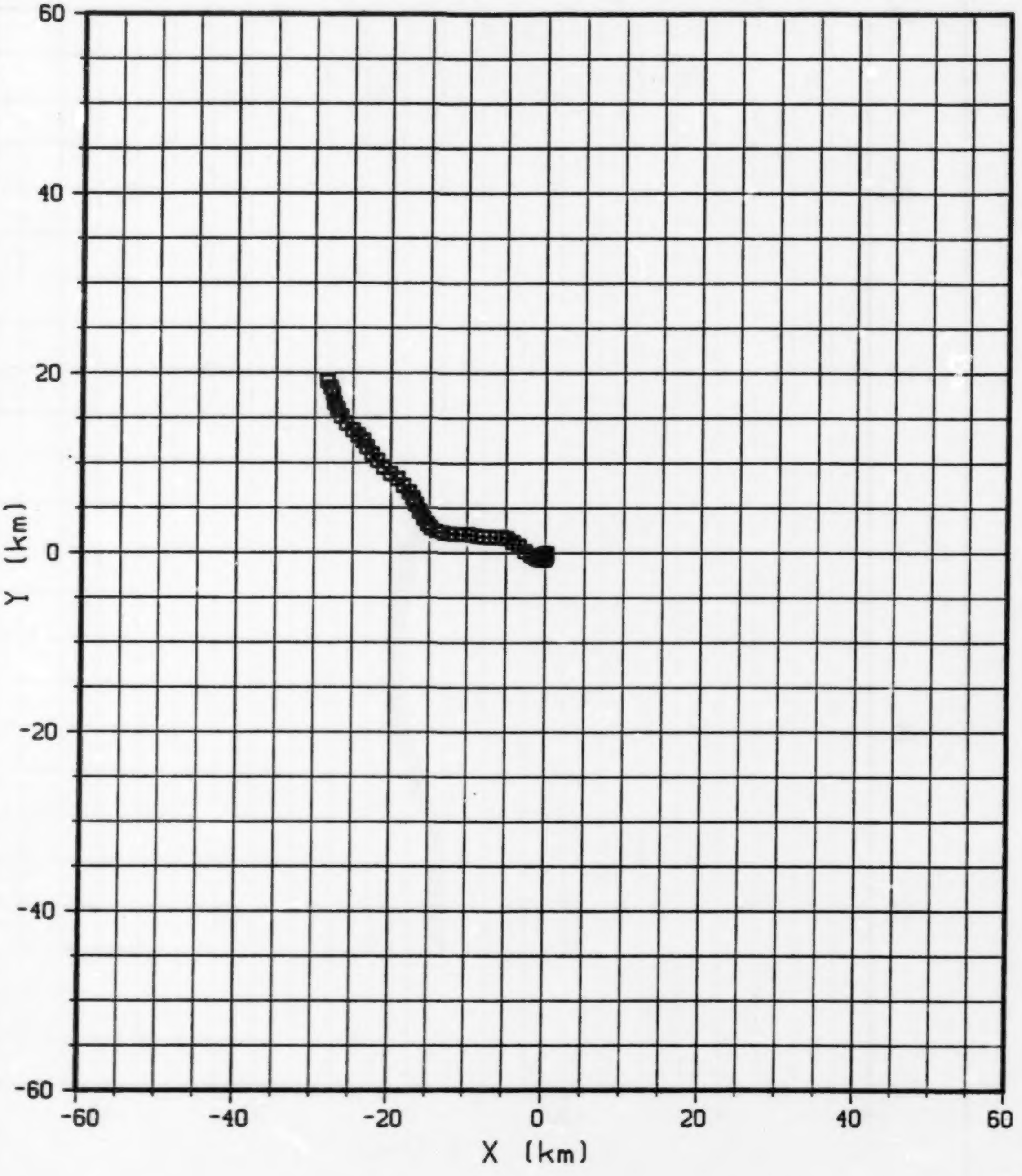


Figure 36. Floating pollutant trajectory, February 21, 1979

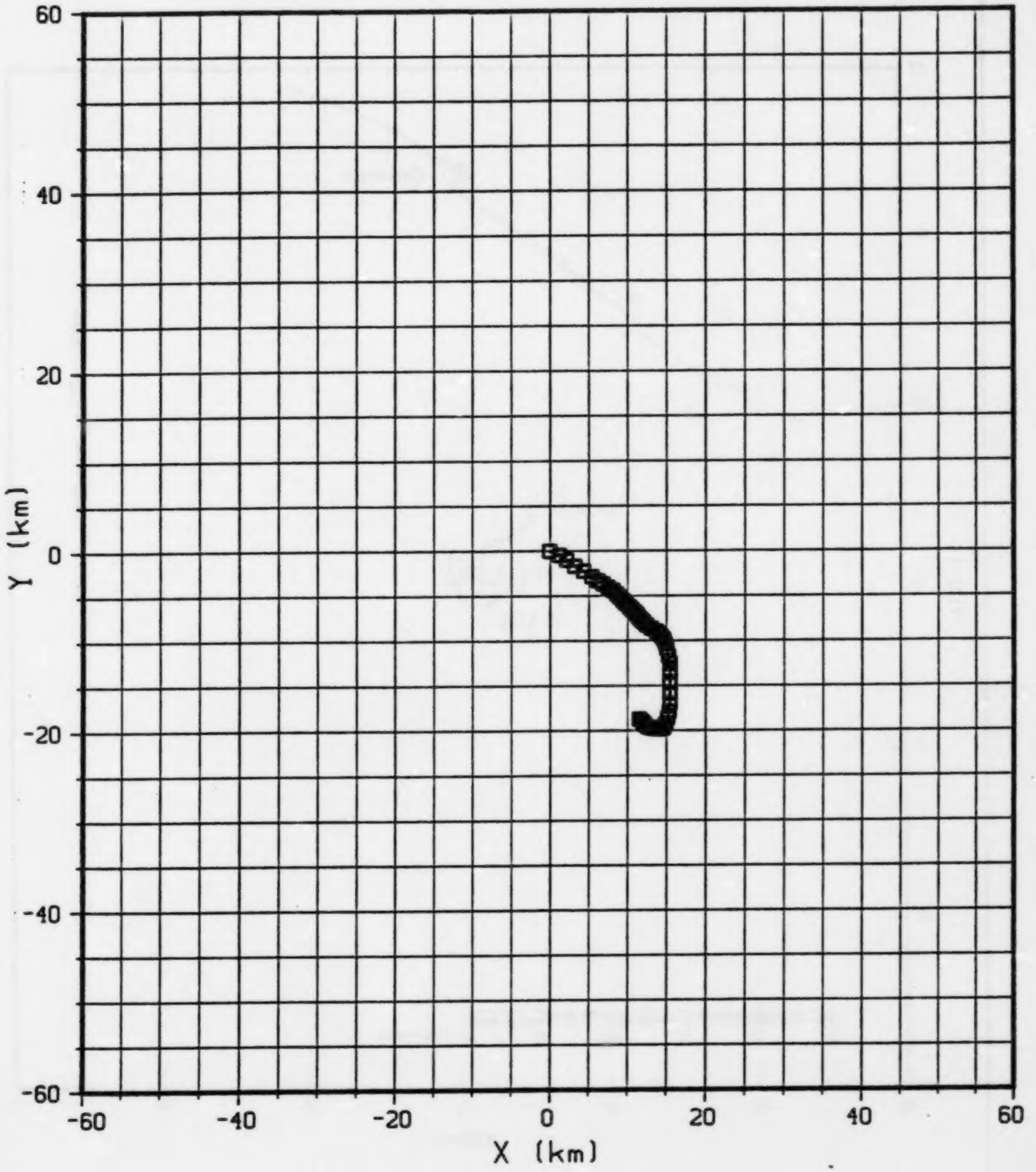


Figure 37. Floating pollutant trajectory, February 25, 1979

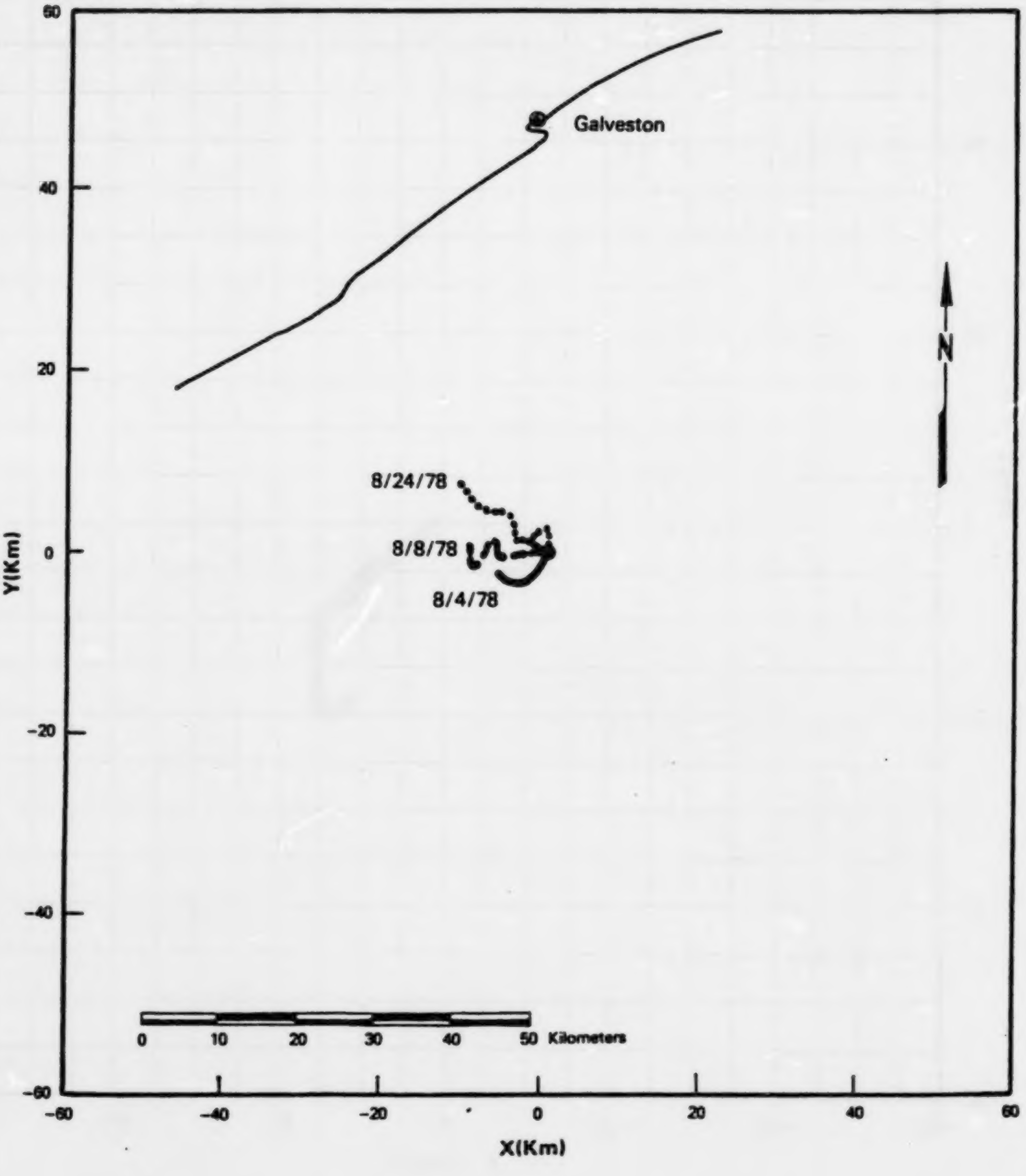

60
40
20
0
-20
-40
-60
Y(Km)
-60
-40
-20
0
20
40
60
X(Km)
Galveston
8/24/78
8/8/78
8/4/78
N
0
10
20
30
40
50 Kilometers

Figure 38. Composite map of floating pollutant trajectories, August 1978

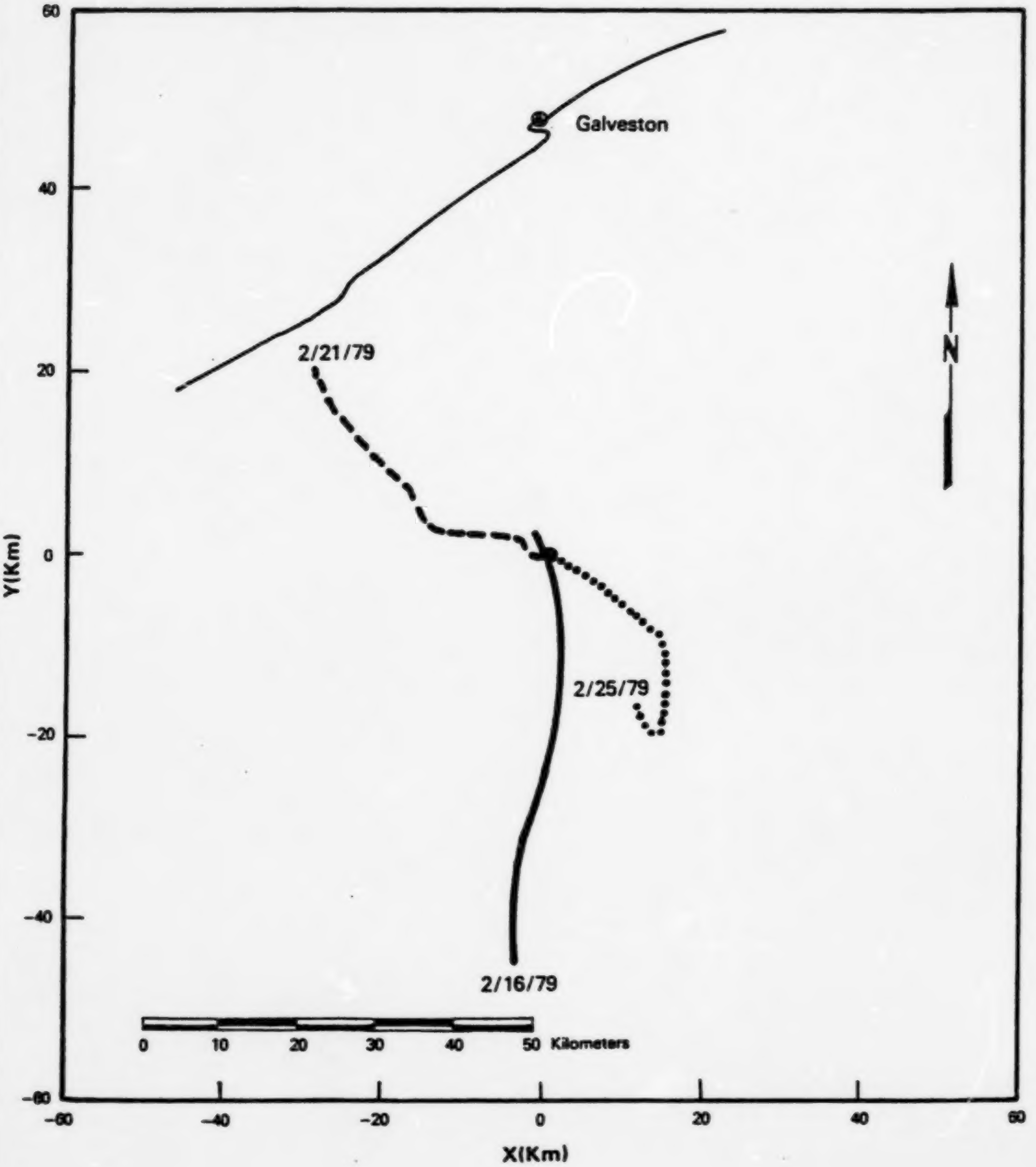

60
40
20
0
-20
-40
-60
Y(Km)
-60
-40
-20
0
20
40
60
X(Km)
Galveston
2/21/79
2/25/79
2/16/79
N
0
10
20
30
40
50 Kilometers

Figure 39. Composite map of floating pollutant trajectories, February 1979